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RELATION OF TEMPERATURE TO THE AMOUNT OF NITROGEN IN SOILS

HANS JENNY

University of Missouri

Received for publication December 8, 1928

INTRODUCTION

In an earlier paper (9) it was shown that in semi-arid and semi-humid regions of the United States, the average nitrogen content of the soil increases two to three times for each 10°C. fall in mean annual temperature. This result agreed with a formula which was developed from the assumption that organic matter produced by vegetation and its destruction by microörganisms is primarily determined by climatic conditions. After a simple S-shaped curve is assumed for the decomposition process in respect to temperature, and when only soils of similar humidity and similar natural vegetation are considered, the equation takes the form:

$$N = \frac{a}{1 + e^{kt}} \qquad (A)$$

where N represents the total nitrogen content of the soil in per cent, t the mean annual temperature, and a, k, constants.

Further material has been collected to support the results already secured. Five new curves are discussed in this paper; namely, curves for humid prairie and humid timber soils, and also curves for semi-humid prairie, terrace, and bottom land soils.

The nitrogen-temperature curves of these soil groups can all be described by the foregoing formula. In spite of this agreement, however, equation (A) represents no more than a first approximation of the true law. It may be considered as a working hypothesis leading to interesting and important practical results. Greater knowledge of the decomposition of organic matter with respect to temperature is needed and more soil analyses from northern latitudes should be secured in order to determine the absolute validity of the equation.

HISTORICAL

Few investigators have published definite statements concerning *functional* relationships of climate and soil nitrogen or soil organic matter. Of course, numerous scientists have assumed a climatic influence and supported their views with more or less convincing figures, obtained mostly from limited districts. Scientists who are working in regions of extreme climatic conditions,

for instance, in semi-deserts, tropics, the frigid zones, and high altitudes, are most interested in these quantitative relationships, since in these regions organic matter occurs either in excessive or deficient amounts, thus attracting particular attention.

Sievers and Holtz (28), on analyzing the soils in Washington, demonstrated that the total nitrogen content of the soil increases with altitude. They attributed this increase to the greater rainfall prevailing in the higher regions. Of much significance is J. C. Russell's (26) experimental curve for the prairie soils of Nebraska, which shows that the average nitrogen content increases logarithmically with increasing rainfall. Fortunately in this investigation temperature was kept nearly constant, although not intentionally so. DeTurk (2), summarizing a nitrogen survey of Illinois soils, expresses the idea that the low nitrogen content of the soils in the southern part of the state is due to the more favorable conditions for decomposition, such as higher temperature and rainfall. Attention should also be called to R. Lang's (12) deductions, although no data are given.

Very suggestive and directly related to this subject is the instructive paper of Senstius (27) who discusses the humus-temperature function in the tropical regions of Java.[1] Senstius, modifying a diagram of Mohr, also assumes an S-shaped curve for the destruction of organic matter. However, he combines regions of various types of vegetation thus complicating the mathematical treatment of the problem. He states with Mohr, as quoted from E. J. Russell (25); "Where the soil temperature is below 20°C., organic matter accumulates, being formed faster than it is decomposed; in the lowlands where the soil temperature exceeds 30°C., the decomposition of organic matter proceeds faster than its formation by vegetation, consequently there is no humus. At about 25°C. the soil humus remains constant." In high altitudes where the annual temperature is below 0°C. the microbiological activity is delayed and the surface soils contain from 20–30 per cent organic matter, in spite of the sparce vegetation (8).

SEMI-HUMID TERRACE SOILS

Semi-humid soils are characterized by the humidity factors[2] 280–380, the limits being, of course, somewhat arbitrarily fixed. One could also choose the annual precipitation-evaporation ratios of Transeau (13), but preference is given to the humidity factor, the application of which is not restricted to the United States alone.

The terracs, often styled "second bottoms" and "bench" lands, include old flood plains which now stand largely above the influence of overflow, the streams having cut their channels to lower levels. In their height above the first bottoms the terraces vary from a few feet to several hundred feet. There is

[1] This paper was not known to the author in 1927.

[2] Precipitation divided by saturation deficit of air (15)

often a series of distinct terraces arranged, one above another in step-like succession. The original vegetation consists mainly of timber. Figure 1 illustrates such conditions in Missouri.

The stream terraces are made up of alluvial material, consisting of deposits washed from slopes and uplands and deposited down stream by overflow waters. The source of this material is very heterogeneous, including wash from loessial, glacial, and a variety of residual soils, both timber and prairie. About 22 different soil series have been included, representing the states of Iowa (7), Missouri (19), and Arkansas (21).

FIG. 1. SCHEMATIC ARRANGEMENT OF FLOOD PLAIN, TERRACE, AND UPLAND

The procedure of calculating the average nitrogen content of the terrace silt loam soils of a county is illustrated by the following example:

Black Hawk County, Iowa. Temperature 46.6°F. Humidity factor about 368

SOIL TYPE	PER CENT OF COUNTY AREA	N	AREA × N	AVERAGE N
		per cent		*per cent*
Waukesha silt loam	3.2	0.195	0.6240	0.7831
Bremer silt loam	0.6	0.242	0.1452	3.9
Calhoun silt loam	0.1	0.139	0.0139	0.201%N
Total	3.9		0.7831	

These county values (units) were classified according to their mean annual temperature class intervals of 2°F. being used. The mean nitrogen values of the various temperature classes were then plotted against the temperature midpoints of the classes and a curve was smoothed with the method of least squares, using the reciprocal mean errors as weights. The constant a was found by tryouts and then k was algebraically computed. The final formula has the expression:

$$N = \underset{\text{Terrace}}{} \frac{1.80}{1 + e^{0.069\,(t\,-\,18.80)}} \qquad (B)$$

where N represents average nitrogen content of the soil in per cent and t the annual temperature F°. Observed and calculated values are summarized in table 1 and the graph is given in figure 2.

Also for terrace soils the N-T relation[3] is remarkably exponential. One

[3] Abbreviation of nitrogen-temperature relation.

wonders whether the uniformity in the distribution of nitrogen is entirely due to temperature or whether the nature of terrace soils consisting of outwash of surrounding upland soils which themselves show the N-T relation did not help to pronounce the relationship.

SEMI-HUMID BOTTOM LAND SOILS

The bottom land soils occur along the banks of the streams in continuous and interrupted strips varying from a few feet wide along the minor drainage courses to broad bottoms several miles wide. The broadest strip of strictly

TABLE 1

Nitrogen-temperature relation in semi-humid terrace soils (silt loams)

Humidity factors 280–380

MEAN ANNUAL TEMPERATURE		STATE	NUMBER OF COUNTIES (UNITS)	NUMBER OF NITROGEN VALUES	AVERAGE NITROGEN CONTENT	CALCULATED VALUE	DEVIATION
°F.	°C.				*per cent*		
44.0	6.67	Iowa	7	9	*0.322* ±0.056	0.269	+0.053
46.0	7.78	Iowa	2	4	*0.249* ±0.049	0.239	+0.010
48.0	8.89	Iowa	17	41	*0.198* ±0.007	0.212	−0.014
50.0	10.00	Iowa Missouri	9	20	*0.181* ±0.011	0.187	−0.006
52.0	11.11	Iowa Missouri	5	7	*0.160* ±0.020	0.165	−0.005
54.0	12.22	Missouri	5	8	*0.113* ±0.013	0.146	−0.033
56.0	13.33	Missouri	7	17	*0.095* ±0.015	0.128	−0.033
58.0	14.14	Missouri	3	8	*0.109* ±0.003	0.113	−0.004
62.0	16.67	Arkansas	4	4	*0.105* ±0.009	0.087	+0.018
64.0	17.78	Arkansas	2	2	*0.072* ±0.003	0.076	−0.004
Temperature range		Total	Total	Total	Nitrogen range	Constants	
20.0	11.11	3	61	120	0.322 to 0.072%	a = 1.80 k = 0.069	

alluvial land is along the Mississippi River near its confluence with the Arkansas River where the bottoms range from 75 to 100 miles wide. These first bottoms are subject to submergence by overflow waters. The surface is dominantly flat and level. Natural vegetation consists predominantly of timber with some meadows and swamps.

The source of all the material entering into the composition of alluvial soils cannot be precisely determined in all cases, but generally speaking, it consists of wash from loessial, glacial, residual, and terrace soils. The bottom land soils are immature because they are being added to by each overflow and also because the time between overflows is insufficient for and the conditions unfavorable to the advancement of those processes of weathering which have brought about

the different characteristics obtaining in older, better drained, normal soils. Oxidation has usually been inhibited by poor drainage (14).

Bottom land soils including 21 series in Iowa (7), Missouri (19), and Arkansas (21), were investigated. The same methods of arranging and computing the data were followed as in the case of terrace soils. Numerical information is given in table 3, graphic representation in figure 2. The equation has the form:

$$N_{\text{Bottom}} = \frac{1.60}{1 + e^{0.075\,(t - 24.00)}} \qquad (C)$$

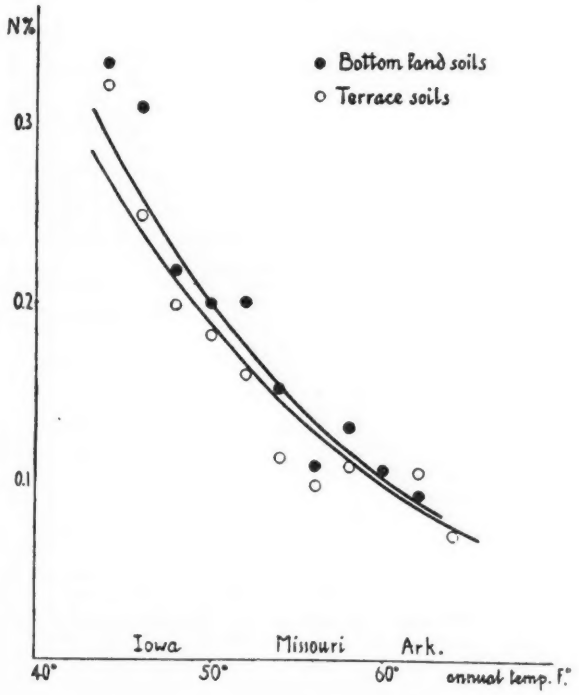

FIG. 2. NITROGEN-TEMPERATURE RELATION IN SEMIHUMID BOTTOM LAND SOILS (UPPER CURVE) AND TERRACE SOILS (LOWER CURVE) FOR SILT LOAMS

The curves of bottom land and terrace soils run nearly parallel, the former lying above the latter. The difference, however, is not important enough to indicate that bottom silt loams contain on the average more nitrogen than the terrace silt loams. The same similarity is observed for the carbon-nitrogen ratio, indicating that in both groups organic matter is equally well decomposed (table 2).

HUMID PRAIRIE AND TIMBER SOILS

East of the Mississippi River the precipitation-evaporation ratio increases slowly. The semi-humid region grades into the humid region. The part of humid region investigated includes southern Wisconsin, Illinois, western Kentucky, western Tennesee, and Mississippi. It is characterized by the humid-

TABLE 2

Carbon-nitrogen ratio in terrace and bottom soils of Iowa

TEMPERATURE		TERRACE SOILS (31 VALUES)	BOTTOM SOILS (31 VALUES)
°F.	°C.		
44.0	6.67	11.97 ±0.286	12.60 ±0.305
46.0	7.78	11.90 ±0.200	11.87 ±0.437
48.0	8.89	12.06 ±0.240	12.33 ±0.348
50.0	10.00	12.40 ± 0.235	11.88 ±0.463
Average.....		12.33 ±0.484	12.17 ±0.787

TABLE 3

Nitrogen-temperature relation in semi-humid bottom land soils (silt loams)

Humidity factors 280–380

MEAN ANNUAL TEMPERATURE		STATE	NUMBER OF COUNTIES (UNITS)	NUMBER OF NITROGEN VALUES	AVERAGE NITROGEN CONTENT	CALCULATED VALUE	DEVIATION
°F.	°C.				*per cent*		
44.0	6.67	Iowa	7	9	*0.327* ±0.040	0.292	+0.035
46.0	7.78	Iowa	2	2	*0.310* ±0.019	0.258	+0.052
48.0	8.89	Iowa	14	20	*0.218* ±0.020	0.227	−0.009
50.0	10.00	Iowa Missouri	9	16	*0.200* ±0.012	0.199	+0.001
52.0	11.11	Iowa Missouri	9	22	*0.202* ±0.016	0.175	+0.027
54.0	12.22	Missouri	12	24	*0.150* ±0.010	0.152	−0.002
56.0	13.33	Missouri	10	16	*0.109* ±0.008	0.133	−0.024
58.0	14.44	Missouri	4	11	*0.131* ±0.010	0.116	+0.015
60.0	15.56	Arkansas	3	7	*0.106* ±0.010	0.101	+0.005
62.0	16.67	Arkansas	2	6	*0.092* ±0.015	0.087	+0.005
Temperature range		Total	Total	Total	Nitrogen range	Constants	
						a = 1.60	
18.0	10.00	3	73	133	0.327 to 0.092%	k = 0.075	

ity factors 300–420. The natural vegetation consists partly of timber and partly of prairie. Only upland soils, particularly silt loam soils, were studied. Fortunately the soil surveys of Wisconsin (32), Illinois (6), and Mississippi (5), separate clearly the prairie and timber soils in the classification, thus permitting the construction of two distinct curves for the entire region. As in the foregoing

examples the nitrogen values were arranged and computed. Figure 3, and tables 4 and 5 give the essential features. The equations have the form:

$$N_{\text{Humid prairie}} = \frac{1.60}{1 + e^{0.056\,(t - 18.20)}} \qquad (D)$$

$$N_{\text{Humid timber}} = \frac{1.00}{1 + e^{0.062\,(t - 18.20)}} \qquad (E)$$

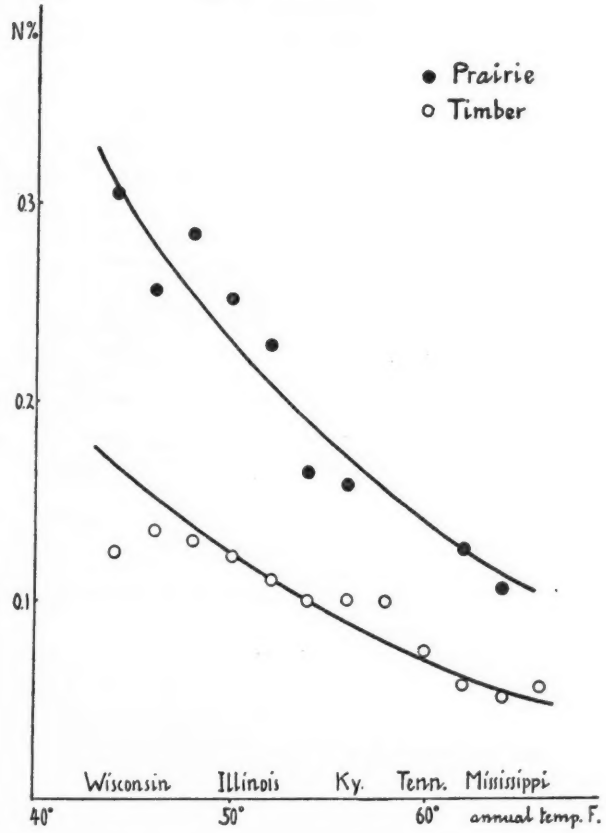

FIG. 3. NITROGEN-TEMPERATURE RELATION IN HUMID PRAIRIE (UPPER CURVE) AND HUMID TIMBER SOILS (LOWER CURVE) FOR SILT LOAMS

The nitrogen content of both prairie and timber soils decreases exponentially with increasing temperature, although this is less pronounced in the case of the timber curve. The well-known superiority of the prairie soils over the timber

soils is remarkably manifested for nitrogen in the entire region. The exact cause of this difference in nitrogen cannot be determined from the present data, since it is not known how much organic matter is produced by the forests of that region. The constants a in the equations (1.60, 1.00), which stand for the

TABLE 4

Nitrogen-temperature relation in humid prairie soils (silt loams)

Humidity factors 300–420

MEAN ANNUAL TEMPERATURE		STATE	NUMBER OF COUNTIES (UNITS)	NUMBER OF NITROGEN VALUES	AVERAGE NITROGEN CONTENT	CALCULATED VALUE	DEVIATION
°F.	°C.				*per cent*		
44.0	6.67	Wisconsin	2	6	*0.304* ±0.028	0.305	−0.001
46.0	7.78	Wisconsin Illinois	4	11	*0.256* ±0.011	0.287	−0.031
48.0	8.89	Illinois	9	9	*0.285* ±0.016	0.254	+0.031
50.0	10.00	Illinois	11	12	*0.252* ±0.009	0.231	+0.021
52.0	11.11	Illinois	8	10	*0.228* ±0.008	0.210	+0.018
54.0	12.22	Illinois	5	7	*0.164* ±0.012	0.190	−0.026
56.0	13.33	Illinois	2	3	*0.158* ±0.020	0.172	−0.014
62.0	16.67	Mississippi	5	16	*0.125* ±0.016	0.127	−0.002
64.0	17.78	Mississippi	6	19	*0.105* ±0.008	0.114	−0.009
Temperature range		Total	Total	Total	Nitrogen range	Constants	
20.0	11.11	4	52	93	0.304 to 0.105%	a = 1.60 k = 0.056	

TABLE 5

Carbon-nitrogen ratio in prairie and timber soils of Illinois (silt loams)

TEMPERATURE		PRAIRIE SOILS (33 VALUES)	TIMBER SOILS (32 VALUES)
°F.	°C.		
48.0	8.89	11.36 ±0.315	11.56 ±0.581
50.0	10.00	12.33 ±0.207	11.21 ±0.258
52.0	11.11	11.79 ±0.229	11.03 ±0.272
54.0	12.22	10.83 ±0.693	11.10 ±0.203
Average.....		11.58 ±0.821	11.23 ±0.721

nitrogen content of the vegetation, suggest that the low nitrogen content of the timber might be partly responsible. It is also possible that the higher moisture content of the timber soils stimulates the decay of organic matter (4). The average carbon-nitrogen ratio is the same for both groups, as is illustrated in table 5.

NITROGEN-TEMPERATURE RELATION IN THE FLAT PRAIRIE SOILS OF MISSOURI

The question may arise as to how large an area must be considered in order to find a nitrogen-temperature relationship. Generally it can be answered that the narrower the annual isothermus run, the smaller the area that may lend itself to such studies.

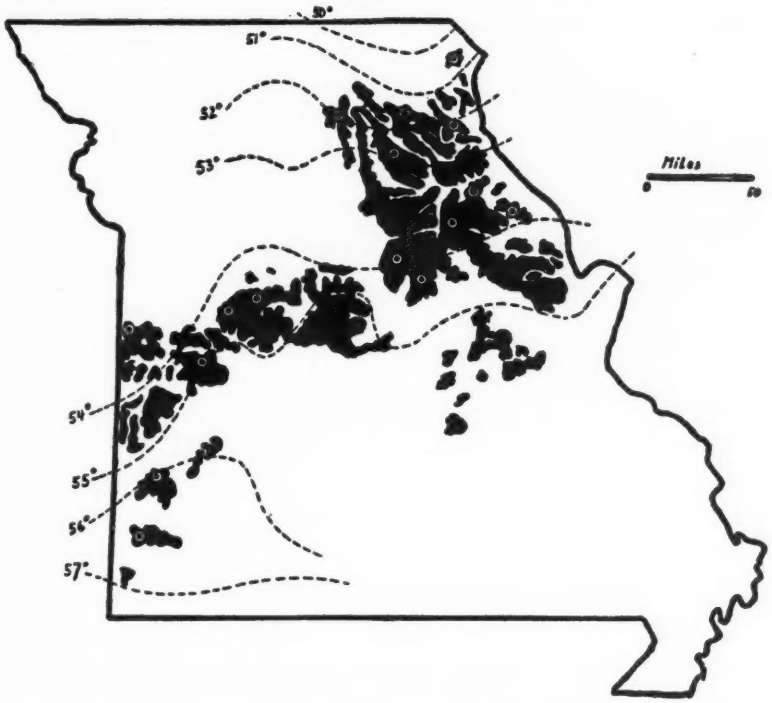

FIG. 4. LOCATION OF FLAT PRAIRIE SOILS IN MISSOURI AND ANNUAL ISOTHERMS IN DEGREES FAHRENHEIT (50°F. = 10.00°C. AND 57°F. = 13.89°C.)

To give a definite answer, the flat prairie soils of Missouri were selected, because they offer a minimum of variation in soil texture, profile, topography, drainage, vegetation, and humidity. The location of these prairie soils, including the soil types Putnam silt loam, Oswego silt loam, and Cherokee silt loam, is shown in figure 4. The area covered has a length from north to south (southern Iowa to southern Missouri) of about 280 miles and an annual temperature range of about 7°F. or about 4°C. (16). Climatic data of surrounding stations are given in table 7. The average nitrogen values for each county are given in

table 8, the graph in figure 5. With so narrow a temperature range it is safe to assume that the nitrogen-temperature relation can be represented by a straight line. After forming temperature classes with intervals of 2°F. and

TABLE 6

Nitrogen-temperature relation in humid timber soils (silt loams)

Humidity factors 300–420

MEAN ANNUAL TEMPERATURE		STATE	NUMBER OF COUNTIES (UNITS)	NUMBER OF NITROGEN VALUES	AVERAGE NITROGEN CONTENT	CALCULATED VALUE	DEVIATION
°F.	°C.				per cent		
44.0	6.67	Wisconsin	3	13	*0.124* ±0.010	0.168	−0.044
46.0	7.78	Wisconsin Illinois	7	33	*0.135* ±0.008	0.151	−0.016
48.0	8.89	Illinois	9	9	*0.130* ±0.007	0.136	−0.006
50.0	10.00	Illinois	10	14	*0.124* ±0.005	0.122	+0.002
52.0	11.11	Illinois	8	12	*0.110* ±0.013	0.110	±0.000
54.0	12.22	Illinois	5	10	*0.099* ±0.007	0.098	+0.001
56.0	13.33	Illinois Kentucky	4	9	*0.102* ±0.007	0.088	+0.014
58.0	14.44	Illinois Kentucky Tennessee	9	15	*0.100* ±0.009	0.080	+0.020
60.0	15.56	Tennessee Mississippi	5	14	*0.074* ±0.008	0.069	+0.005
62.0	16.67	Mississippi	5	12	*0.057* ±0.006	0.062	−0.005
64.0	17.78	Mississippi	7	20	*0.051* ±0.003	0.055	−0.004
66.0	18.89	Mississippi	3	20	*0.056* ±0.012	0.051	+0.005
Temperature range		Total	Total	Total	Nitrogen range	Constants	
22.0	12.22	5	75	185	0.135 to 0.051%	a = 1.00 k = 0.062	

TABLE 7

Climatological data of stations surrounding the Missouri flat prairie soils

STATION	ALTITUDE		MEAN ANNUAL TEMPERATURE		HUMIDITY FACTOR
	feet	*meters*	°F.	°C.	
Keokuk, Iowa	614	187	52.3	11.28	336
St. Joseph, Mo.	967	294	54.0	12.22	261
Columbia, Mo.	784	239	54.5	12.50	354
Kansas City, Mo.	963	293	54.8	12.67	276
Springfield, Mo.	1,224	344	55.6	13.11	352
St. Louis, Mo.	567	173	56.0	13.33	291

nitrogen classes with intervals of 0.02 per cent N, a correlation coefficient (r) of −0.77 can be computed. It expresses the degree to which the two variables, nitrogen and temperature, tend to be associated. Perfect correlation would

give a value of -1.00; no correlation, a value of zero. With the aid of the correlation coefficient the line of best fit can easily be calculated. It has the form:

$$N = -0.0131\, t_{49^\circ}^{57^\circ} + 0.8522$$

where N represents the average nitrogen content of the soil in per cent and t the mean annual temperature in °F. (49°F.–57°F.).

Summarizing we may state that the N-T relation can be clearly demonstrated within a region as small as that covered by the flat prairie soils of Missouri.

TABLE 8

Nitrogen temperature relation in the flat prairie soils of Missouri

Humidity factors 261–354

MEAN ANNUAL TEMPERATURE		COUNTY	NUMBER OF NITROGEN VALUES	AVERAGE TOTAL NITROGEN CONTENT	SOIL TYPE
°F.	°C.			*per cent*	
49	9.44	Wapello, Ia.	1	0.222	Putnam silt loam
51	10.56	Clark, Mo.	1	0.158	Putnam-like Grundy
52	11.11	Knox, Mo.	4	0.178	Putnam silt loam
52	11.11	Harrison, Mo.	3	0.206	Putnam silt loam
52.3	11.28	Lee, Iowa	1	0.177	Putnam silt loam
53	11.67	Rolls, Mo.	3	0.119	Putnam silt loam
53	11.67	Shelby, Mo.	8	0.169	Putnam silt loam
53.4	11.89	Cass, Mo.	1	0.133	Oswego silt loam
53.5	11.94	Marion, Mo.	10	0.145	Putnam silt loam
53.5	11.94	Macon, Mo.	9	0.157	Putnam silt loam
53.5	11.94	Pike, Mo.	1	0.135	Putnam silt loam
53.7	12.06	Audrien, Mo.	4	0.142	Putnam silt loam
54.4	12.44	Pettis, Mo.	6	0.152	Oswego silt loam
54.5	12.50	Boone, Mo.	1	0.118	Putnam silt loam
54.9	12.72	Callaway, Mo.	3	0.155	Putnam silt loam
55	12.78	Johnson, Mo.	2	0.161	Oswego silt loam
55.6	13.06	Henry, Mo.	8	0.121	Cherokee silt loam
56.4	13.56	Barton, Mo.	1	0.100	Cherokee silt loam
57.2	14.00	Newton, Mo.	1	0.122	Cherokee silt loam

The carbon-nitrogen ratio

Equation A for nitrogen should hold as well for oganic matter expressed as total organic carbon. One has only to put C in the place of N in the formula and adjust the constants. The approximate amount of organic carbon can be found by multiplying the percentage of nitrogen by 10, which is based upon the fact that in temperate regions the carbon-nitrogen ratio in the soil is about 10 (31). This ratio seems to vary somewhat with temperature, since it is wider in the north than in the south, as shown in table 9 and figure 6. Because of the limited amount of data, both the semi-arid and semi-humid regions were included (3, 7, 10, 26, 29).

The functional change of the C/N ratio seems to support the general character of equation *A*, which demands that under low temperatures the nitrogen content of the soil approaches the nitrogen content of the vegetation (constant *a*) and consequently, the C/N ratio of the soil tends to become as wide as that of the undecomposed organic material.

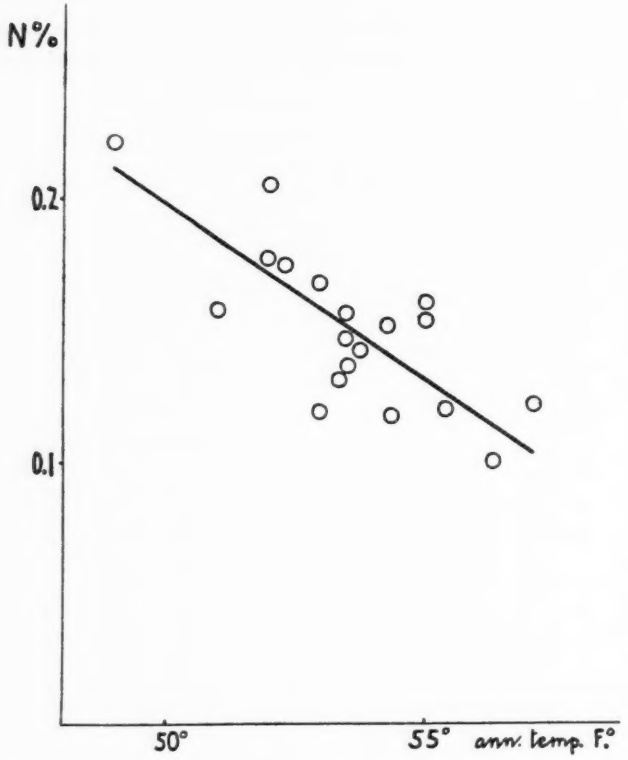

FIG. 5. NITROGEN-TEMPERATURE RELATION OF THE FLAT PRAIRIE SOILS OF MISSOURI

DISCUSSION

Temperature

Whether the nitrogen temperature equation is expressed in units Fahrenheit or Centigrade or in absolute units starting with −273°C., does not matter, as they can easily be converted. More important is the choice of the meteorological unit, since no soil temperatures are available. Shall the nitrogen content be related to the annual temperature, to the number of months or days having

temperatures above the freezing point, or to some other criterion of the heat effect, such as frost, free season, or daily temperature summations?

TABLE 9

Carbon-nitrogen ratio and temperature (loams and silt loams)

TEMPERATURE		STATE	C/N	NUMBER OF VALUES (COUNTIES)
°F.	°C.			
35.0	1.67	Saskatchewan (Canada)	13.25 ±0.555	6
44.0	6.67	Iowa	12.21 ±0.210	10
46.0	7.78	Iowa	12.30 ±0.122	4
48.0	8.89	Iowa	11.85 ±0.191	19
50.0	10.00	Iowa Nebraska	12.11 ±0.136	14
52.0	11.11	Nebraska	11.90 ±0.383	4
54.0	12.22	Nebraska Kansas	11.15 ±0.470	6
57.0	13.89	Kansas	10.30 ±0.681	3
68.0	20.00	Texas	9.1	76

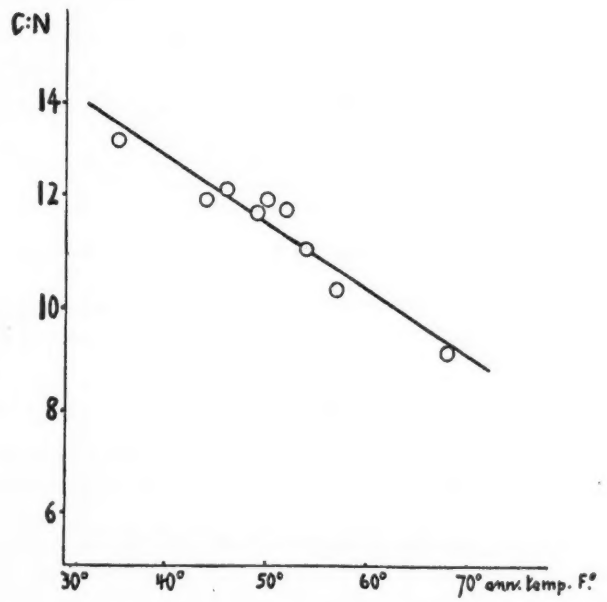

FIG. 6. CARBON-NITROGEN RATIO AND TEMPERATURE IN GRASSLAND SOILS

The mean annual temperature was chosen because it is the easiest value to obtain from meteorological stations (30). Its use, however, is restricted to regions having similar marches of annual temperatures. That this is the case in the states investigated is shown by figure 7, where the annual march of temperature in the latitudes 29° to 49° is illustrated (Kincer).

The deviation of the nitrogen values

The dots in the various N-T diagrams represent averages of their respective temperature classes. The question naturally arises as to how widely the single values are scattered about the average. Are these class-means reliable enough to be put in a function of temperature? Information is obtained from the mean error (or probable error, which is 0.6745 times the mean error) for the class-

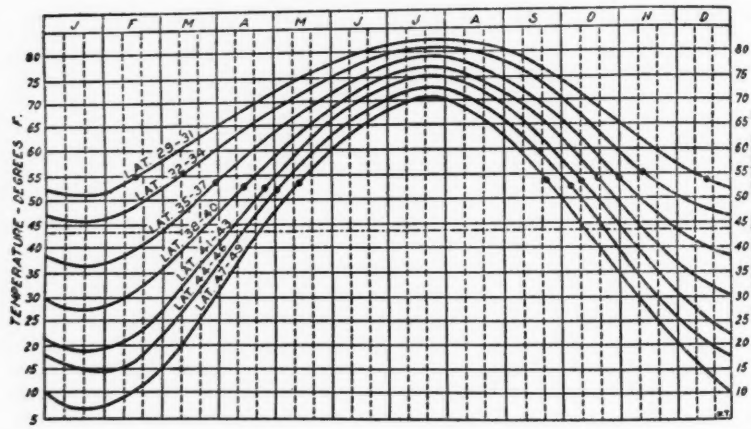

FIG. 7. ANNUAL MARCH OF TEMPERATURE OF THE INVESTIGATED REGIONS (AFTER KINCER)

averages, and from the correlation-ratio for the deviation of the values about the curve. The mean error was calculated according to the common formula:

$$m = \sqrt{\frac{\Sigma v^2}{n(n-1)}}$$

where m represents mean error, n total number of values, and Σv^2 the sum of the squares of the numbers formed by subtracting each value from the arithmetical mean of the whole class.

As an index of the deviation of the single nitrogen values (county units) about the curve, the correlation ratio was chosen (18). It measures the degree of relationship between the single nitrogen values and the corresponding temperature in so far as this relationship may be described by a curve passing through the mean of every temperature class. If the relationship is ideal, if there is no

scatter about the curve fitted in this way, η will have a value of 1. If there is no relationship, if the scatter about the curve is as great as the dispersion about the mean of all nitrogen values, η will have a value of zero. The formula used is

$$\eta = \sqrt{1 - \frac{\sigma_{NT}^2}{\sigma_N^2}}$$

TABLE 10

Correlation-ratio of the various soil regions

CURVE	η
Semi-arid region, grassland	0.91
Semi-humid upland soils (predominating prairie)	0.90
Semi humid terrace soils (predominating timber)	0.78
Semi-humid bottom soils (timber)	0.78
Humid upland soils (prairie)	0.89
Humid upland soils (timber)	0.84
Flat prairie soils of Missouri	0.77

TABLE 11

Nitrogen-temperature relation in the semi-arid region

Humidity factors 125–250

MEAN ANNUAL TEMPERATURE		STATE	NUMBER OF COUNTIES (UNITS)	NUMBER OF NITROGEN VALUES	AVERAGE NITROGEN CONTENT	CALCULATED VALUE	DEVIATION
°F.	°C.				*per cent*		
32[a]	0.0	Canada	....	10	*0.44*[b]	0.344	+0.096
36	2.22	Canada N. Dakota	5	30	*0.295* ±0.050	0.297	−0.002
38	3.33	N. Dakota	4	5	*0.291* ±0.032	0.276	+0.015
40	4.44	N. Dakota	5	12	*0.244* ±0.015	0.256	−0.012
42	5.56	N. Dakota	1	1	*0.21*[b]	0.237	−0.027
48	8.89	Nebraska	2	17	*0.199* ±0.0077	0.187	+0.012
50	10.00	Nebraska	7	28	*0.192* ±0.012	0.172	+0.020
55	12.78	Kansas	6	47	*0.152* ±0.022	0.140	+0.012
58	14.44	Texas	12	32	*0.100* ±0.0065	0.124	−0.024
60	15.56	Texas	3	8	*0.081* ±0.022	0.114	−0.033
64	17.78	Texas	3	27	*0.085* ±0.012	0.096	−0.011
66	18.89	Texas	2	40	*0.112* ±0.010	0.088	+0.024
68	20.00	Texas	3	25	*0.063* ±0.0091	0.081	−0.018
70	21.11	Texas	13	48	*0.075* ±0.0076	0.075	−0.000
72	22.22	Texas	5	18	*0.075* ±0.0040	0.068	+0.007
Temperature range		Total	Total	Total	Range	a = 1.70	
40°	22.22°	5	71	348	0.44 to 0.063%	k = 0.045	

[a] Temperature estimated.

[b] Not used in calculating the constants.

Where η represents correlation ratio, σ_{NT} the standard deviation of all single nitrogen values about a line passing through the mean of the various temperature classes, and σ_N the standard deviation of all single nitrogen values about their arithmetical average. This correlation ratio of the various soil regions is listed in table 10. Generally speaking, the correlation ratio is about 0.85, indicating that a nitrogen-temperature relation is pronounced.

The deviation of nitrogen values may be due to errors in sampling (variations in depth) or to factors which hasten or delay the decomposition process in the

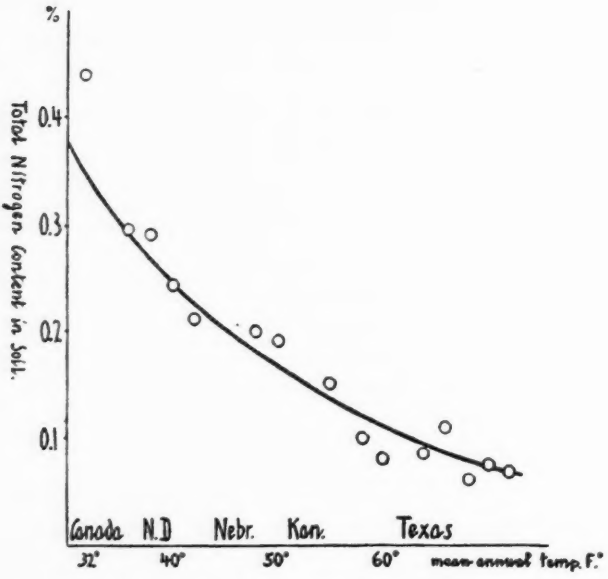

FIG. 8. AVERAGE TOTAL NITROGEN CONTENT OF THE SOIL AS RELATED TO THE MEAN ANNUAL TEMPERATURE IN THE SEMI-ARID REGION

field above or below "normal." Such factors are physical and chemical properties of the soil, age, topography, geological origin, soil climate, vegetation, and cultivation.

Nitrogen turn-over

Virgin prairie soils have a nitrogen content of about 20 to 40 per cent higher than that of cultivated prairie soils which have been cropped for 30 to 40 years. A simultaneous decrease of fertility is demonstrated by the rapidly decreasing yields of untreated experiment plots.

Often the idea is expressed that nitrogen and organic matter should be

restored by adding sufficient amounts of green manure and stable manure. In several publications a nitrogen content of 0.250 to 0.300 per cent nitrogen is given as a desirable value for a fertile soil. This figure corresponds to the nitrogen content of Minnesota, Iowa, and northern Illinois prairie soils.

TABLE 12

Nitrogen-temperature relation in the semi-humid region (upland soils)

Humidity factors 280–380

MEAN ANNUAL TEMPERATURE		STATE	NUMBER OF COUNTIES (UNITS)	NUMBER OF NITROGEN VALUES	AVERAGE NITROGEN CONTENT	CALCULATED VALUE	DEVIATION
°F.	°C.				*per cent*		
32[a]	0.00	Canada	.....	16	*0.475*[b]	0.455	+0.020
34	1.11	Canada	1	17	*0.393* ±0.023	0.414	−0.021
36	2.22	N. Dakota	7	20	*0.341* ±0.017	0.376	−0.035
38	3.33	N. Dakota	4	6	*0.341* ±0.083[b]	0.340	+0.001
40	4.44	N. Dakota	10	32	*0.295* ±0.017	0.307	−0.012
42	5.56	Minnesota	7	17	*0.273* ±0.018	0.276	+0.003
44	6.67	Minnesota	16	44	*0.266* ±0.012	0.248	+0.018
46	7.78	Minnesota Iowa	11	23	*0.266* ±0.014	0.222	+0.044
48	8.89	Iowa	9	26	*0.210* ±0.014	0.198	−0.012
50	10.00	Iowa Missouri	21	54	*0.172* ±0.0050	0.177	−0.005
52	11.11	Iowa Missouri	11	60	*0.168* ±0.0070	0.160	+0.008
54	12.22	Missouri Kansas	10	56	*0.150* ±0.012	0.140	+0.010
56	13.33	Missouri	13	56	*0.101* ±0.0094	0.124	−0.023
58	14.44	Missouri Arkansas	9	20	*0.098* ±0.0095	0.110	−0.012
60	15.56	Arkansas	8	8	*0.091* ±0.0081	0.098	−0.007
62	16.67	Arkansas	3	3	*0.078* ±0.0057	0.086	−0.008
66	18.89	Louisiana	3	6	*0.056* ±0.0015	0.067	−0.011
68	20.00	Louisiana	4	11	*0.050* ±0.0064	0.059	−0.009
Temperature range		Total	Total	Total	Range	a = 1.55	
36°	20.00°	9	147	475	0.475 to 0.050%	k = 0.065	

[a] Temperature estimated.

[b] Not used in calculating the constants.

From the nitrogen temperature curves it is obvious that the building up of nitrogen in the soil meets greater difficulties the farther south one goes. As a matter of fact 20 to 30 years of manuring experiments in southern states have failed to secure any considerable increase in soil nitrogen. Even as far north as Wooster, Ohio (mean annual temperature 49°F.), it has not been possible to reach the original nitrogen content of the unbroken soil (22).

Recently the term "nitrogen turn-over" has been suggested, a term which refers to the amount of nitrogen that may be supplied to crops from rotation to rotation by means of crop residues, green manures, and farm manures (17).

Results of earlier work

For the sake of completeness two curves and tables previously obtained are included. Table 11 and figure 8 refer to soils of various textures of the semi-

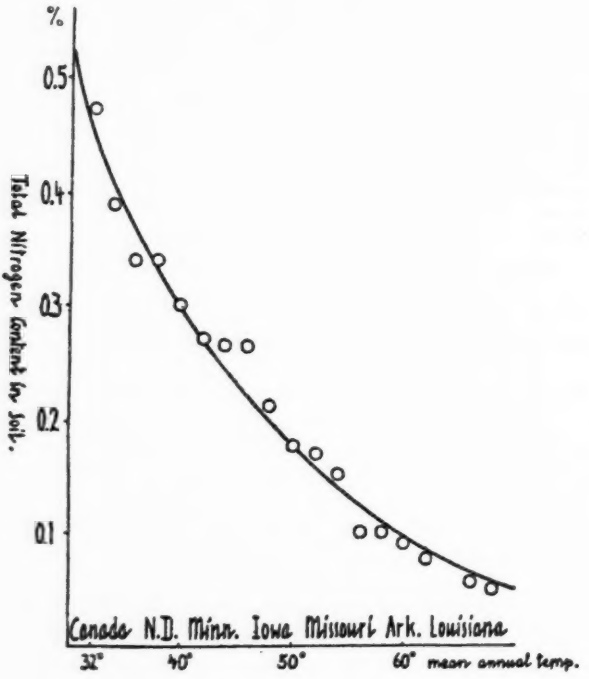

FIG. 9. AVERAGE TOTAL NITROGEN CONTENT OF THE SOIL AS RELATED TO THE MEAN ANNUAL TEMPERATURE IN THE SEMI-HUMID REGION (UPLAND SOILS)

arid grassland region lying within the Great Plains. Table 12 and figure 9 show the N-T relation in the semi-humid region for upland soils (loams and silt loams). The original predominating vegetation is tall prairie grass. The values above 50°F. (which were not used in calculating the constants) represent soils with original forest vegetation mainly of oaks. These values are somewhat below the theoretical grass land values for that part of the curve.

SUMMARY

1. In the semi-arid, semi-humid, and humid regions of the United States a correlation exists between the mean annual temperature and the average total nitrogen content of upland prairie and timber soils and of terrace and bottom land soils.

2. The decrease of nitrogen with increase of temperature is exponential or, in other words, the logarithm of the nitrogen varies inversely to the temperature.

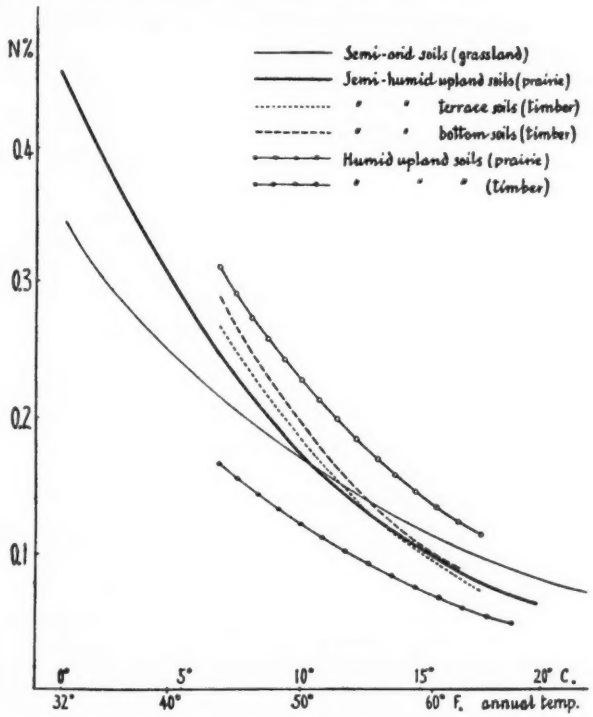

FIG. 10. GRAPHIC SUMMARY OF NITROGEN-TEMPERATURE RELATIONS

Generally speaking, for every 10°C. decline in mean annual temperature, the average nitrogen content of the soil increases two to three times (fig. 10).

3. The carbon-nitrogen ratio of the soil organic matter seems to become narrower with increasing temperature.

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THE RELATION BETWEEN CONCENTRATIONS OF POTASSIUM IN CULTURE SOLUTIONS AND OPTIMUM PLANT GROWTH[1]

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Potassium fertilizers at the present time are applied largely because of soil needs. Some attempt has been made to consider the needs of the plants, as determined by their chemical analyses. The different crops have been grouped into general classes in accordance with their need for large amounts of potassium (alfalfa and sweet clover) or for only small amounts (oats and wheat). Although such groupings are undoubtedly very helpful in making recommendations for potassium fertilizers, they are too general to be of much value. Moreover, although they establish the approximate total amount of potassium needed by the plants they do not give any index as to the amount of available potassium which must be present in solution in the nutrient media during the life of the plant.

It is well known that plants immediately use only soluble constituents. Hence it might be logical to assume that the composition of the soil solution should give some indication as to the amounts of potassium available for plant nutrition. Reports of several investigations showed a wide variation in the potassium content of the soil solution. Hibbard (13), working with alkali soils, found variations from 21 p.p.m. to 2110 p.p.m. of potassium in the soil solution. Millar (20), from analyses of displaced solutions from soils of the humid region, reports variations of 2.5 p.p.m. to 6.2 p.p.m. potassium for silt loam soils, 1.4 p.p.m. to 2.6 p.p.m. for sands, and 15.3 p.p.m. to 41.0 p.p.m. for peats. Unfortunately we have no good method for determining the rate of availability, and the figures given above show only the initial concentration when the amount in solution is in equilibrium with the relatively insoluble compounds.

If a knowledge of the minimum concentration of potassium required for the maximum growth of a plant could be combined with a knowledge of the concentration of potassium in the soil solution and the ability of the insoluble compounds to maintain that concentration, a good basis for potash fertilization could be established.

The work reported in this paper had for its object the solution of the following

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questions: 1. What are the minimum concentrations of potassium essential for plant growth? 2. Will plants assimilate more potassium than the amount required for optimum growth?

MINIMUM POTASSIUM REQUIREMENTS

In a preliminary report the writers (3) noted that there was considerable variation in the concentrations of potassium necessary to obtain maximum growth of the different crops. Parker and Pierre (22) report from the results of their experiments that the maintenance of a concentration of 2 p.p.m. of potassium would probably be sufficient for the best growth of corn and soybeans.

PLAN OF EXPERIMENT

The seeds were germinated in quartz sand which contained very little, if any, of the soluble plant-food constituents. When the plants were two to three inches high they were transferred to culture solutions. The plants were placed through one-inch holed in paraffined boards and held in place by means of cotton plugs. The boards were then placed over 2-gallon jars filled with nutrient solution containing different amounts of potassium.

IMPORTANCE OF PROPER NUTRIENT SOLUTION

The selection of the proper nutrient solutions for studies of the requirements of plants for any one element is of great importance. If any element were included in the solution which might have some indirect effect on another element it would greatly impair the value of the results obtained.

Many of the standard nutrient solutions contain some compounds of sodium. Because of the similarity of the chemistry of sodium and potassium the question arose as to the effect of the presence of sodium on the assimilation of potassium by plants.

A review of the literature on the value of sodium in plant nutrition was made in order to determine whether the presence of sodium in a nutrient solution would greatly affect the results of a study of the potassium requirements of plants. Doll (7) grew barely in pot cultures composed of one-third sandy soil and two-thirds pure river sand fertilized with sodium chloride, potassium chloride, and mixtures of the two. He concluded that sodium chloride was only slightly less effective than potassium chloride for the nutrition of crops. Gerlach (8) concluded from field experiments that sodium can partially replace potassium when the amounts of potassium are insufficient for normal plant growth. Hartwell (9) from solution experiments with wheat seedlings, obtained a 10 per cent increase in yield from an application of sodium chloride. He concluded that certain functions of potassium in plants can be performed by sodium. On the other hand, he claims that certain functions of potassium can not be performed by sodium and without sufficient potassium for these needs, maximum growth will not be obtained. Somewhat similar results are reported

by Hartwell and Damon (10) from field experiments. Pfieffer (23) states that if there is a deficiency of potassium for the whole plant, sodium will replace potassium in the leaves and stalks and make the potassium available for the grain. Kruger (18), from the results of pot experiments with beets, concludes that sodium can not physiologically replace potassium although its presence permits plants to use increased quantities of potassium more readily. Atterberg (1), from experiments with oats, thought that potassium was partially replaced by sodium. Hoagland (14) and Breazeale (6) concluded that the presence of sodium depressed the intake of potassium by plants. Reed and Haas (24), who studied the effect of sodium on the growth of young orange trees, concluded that sodium can not replace potasssium in plant processes. The trees fertilized with sodium made good growth but the authors decided that the potassium had been transferred from the roots to the leaves. Jordan and Genter (16) also concluded, from the results of pot experiments, that sodium can not perform the function of potassium. Stahl and Schroeder (26) hold the same view. They concluded from the results of pot cultures in which they grew buckwheat, carrots, peas, and oats, on potassium deficient peat, that the increased yields from the sodium treatment over the no treatment jars were insignificant. The foregoing does not cover a complete review of the literature, but sufficient evidence is presented to show that the presence of sodium in a nutrient solution in which the potassium requirements of plants are to be studied may give erroneous results.

Because of the fact that many of the standard nutrient solutions, such as Shive's (25), Knop's (17), and Tottingham's (27) contain sodium, or contain potassium in combinations which are not readily adjusted for varying the concentrations, a suitable nutrient solution had to be devised. The first nutrient solution used was a modified form of that used by Hartwell and Wheeler (11) and contained the following salts: Solution I: Ca $(NO_3)_2 \cdot 4H_2O$, 147 gm.; CaH_4 $(PO_4)_2 \cdot H_2O$, 26.9 gm.; dissolve and make to 2280 cc. Solution II: $MgSO_4 \cdot 7H_2O$, 90 gm.; dissolve and make to 2280 cc.

To each jar, containing 7.5 liters of distilled water, 50 cc. each of solutions I and II were added. Preliminary experiments with this nutrient solution and the one reported in the following, has shown that the concentrations of salts indicated were more than sufficient to maintain normal growth during the intervals between renewals, when sufficient potassium was added to the solution. Therefore in the experiments reported hereafter, potassium was the only element limiting plant growth, and any increase in the amount of dry matter produced by increasing the concentrations of potassium can be attributed only to the increase in the concentration of potassium.

The potassium was added as needed from two solutions of KCl. One solution contained 28.62 gm. of pure KCl per 2000 cc. This was equivalent to 14.997 gm. of K per 2000 cc., or 0.0075 gm. of K per cc. When 1 cc. of this solution was diluted to 7500 cc. the concentration became 1 mgm. of K per liter, or 1.0 p.p.m. The other solution contained 2.862 gm. of pure KCl per

2000 cc. This concentration is equivalent to 0.00075 gm. of K per cubic centimeter. One cubic centimeter of this solution diluted to 7500 cc. produced a concentration of 0.1 mgm. of K per liter or 0.1 p.p.m. The concentration of potassium used varied from 0 mgm. to 50 mgm. of K per liter of nutrient solution. In further discussion, in order to eliminate repetition, the term "concentration of so many p.p.m. of K," means mgm. of K per liter of nutrient solution.

Oats and alfalfa grew very well on this solution. Soybeans and tomatoes grew well for a while but eventually became very chlorotic. This affected the growth to such an extent that the results could be considered as of only a qualitative nature. After several attempts to grow soybeans and tomatoes in this solution failed, several different solutions were tried with varying results. The one finally adopted was one based on the solutions devised by Hoagland and Martin (15) and Parker (21). The solutions used were: Solution A: 807 gm. $Ca(NO_3)_2 \cdot 4H_2O$, 143 gm. $Mg(NO_3)_2 \cdot 6H_2O$, 5 gm. $CaCl_2$, 4 gm. $MgCl_2$, 1 gm. H_3BO_3, water to make 2 liters; Solution B: 300 gm. $MgSO_4 \cdot 7H_2O$, 1.2 gm. $MnSO_4$, water to make 2 liters; Solution C: 7gm. $CaH_4(PO_4)_2 \cdot H_2O$, water to make 2 liters.

Three separate solutions are necessary to prevent precipitation of some of the constituents. Ten cubic centimeters each of solutions A, B, and C were added to 7.5 liters of distilled water. This concentration, as has also been demonstrated by Parker (21), was more than sufficient to supply the needs of the plants for these elements during the periods between renewal of the concentration of these minerals.

The potassium was added from two solutions of KCl of the concentration previously given. The potassium concentration was renewed twice a day according to the following method. Two jars were filled with distilled water and the nutrient solutions, with the exception of potassium, added. The plants were then transferred from the old solution containing no potassium. Sufficient potassium as potassium chloride was added in solution to bring the concentration of the old no potassium treatment to 0.5 p.p.m. of potassium. The solution was well mixed and aerated by stirring with a wooden paddle. To the old 0.5 p.p.m. jars an amount of potassium chloride equivalent to 0.5 p.p.m. was added and it became the new 1.0 p.p.m. jar to which the 1.0 p.p.m. plants were then transferred. Similarly, amounts equivalent to 1 p.p.m. of potassium were added to the old 1 p.p.m. jars and they became the 2 p.p.m. jars. A similar process was repeated until all the plants had been transferred to a renewed potassium concentration. The same kind of procedure was employed every time the solutions were changed. By using this procedure the potassium concentration was renewed twice a day and all other nutrients, excepting iron, were renewed once every three days.

It was impossible to keep the concentrations exactly up to standard by this procedure because of the feeding of the plants. However, as there are no methods of chemical analysis for the rapid determination of potassium, the

procedure mentioned above would probably be as accurate as analyzing the solutions once every few days and adding the same amount each day, assuming that the daily potassium consumption between periods of analyses was uniform.

In order to add sufficient iron for normal growth the following procedure was adopted. Every third day the pH of the jars containing no potassium was reduced to 4.0 by the addition of dilute hydrochloric acid, and 50 cc. of a 0.5 per cent solution of ferric tartrate added. Therefore as the plants were rotated for the different potassium concentrations they received the necessary amount of iron. In this way no plant was kept in a solution of pH 4.0 for over 12 hours and the possibility of injurious action due to such an acid reaction was reduced. The plants were all grown until they started to blossom, when they were harvested and first air-dried, then oven-dried, and then weighed.

The crops used in this study were oats, alfalfa, Hubam clover, cowpeas, soybeans, Sudan grass, and cotton. In order to reduce as much as possible the

TABLE 1

Oven-dry weights of plants grown in nutrient solutions with concentrations of potassium indicated

K IN SOLUTION	OATS, WEIGHT OF 4 PLANTS		ALFALFA WEIGHT OF 4 PLANTS		HUBAM CLOVER, WEIGHT OF 12 PLANTS	COWPEAS WEIGHT OF 8 PLANTS		SOY-BEANS, WEIGHT OF 8 PLANTS	SUDAN GRASS, WEIGHT OF 12 PLANTS		COTTON, WEIGHT OF 8 PLANTS
	Tops	Roots	Tops	Roots	Tops	Tops	Roots	Tops	Tops	Roots	Tops
p.p.m.	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*
0.0	1.0	0.7	0.26	0.07	0.85	5.5	2.4	3.75	5.3	1.4	4.6
0.5	10.0	3.3	3.40	1.60	1.90	24.9	8.3	11.85	45.1	6.1	8.0
1.0	10.9	3.5	2.70	1.20	1.71	30.6	9.4	10.05	53.4	5.2	9.3
2.0	14.5	4.8	2.80	1.40	1.72	35.1	10.2	14.10	43.3	8.3	12.4
3.0	9.8	3.3	3.20	1.70	1.75	32.8	9.4	13.65	71.1	7.2	12.7
5.0	7.1	2.2	2.90	1.40	1.95	43.0	13.2	15.45	72.0	13.8	13.3
10.0	11.9	2.9	.....	.....	.....	.....	.....	.....	.....	.....	.....
25.0	10.8	2.8	.....	.....	.....	.....	.....	.....	.....	.....	.....
50.0	10.6	3.2	.....	.....	.....	.....	.....	.....	.....	.....	.....

error which might be caused by plant variation, the plants were grown at the rate of two to six plants per jar, depending on the crop. Because of the differences in the plants used the different ones will be discussed separately.

OATS

The oats grew very rapidly after being transferred to the culture solutions. They tillered very profusely and were harvested after growing in the culture solutions for 50 days. The yields are given in table 1.

There is no definite correlation between the root growth and the top growth. In a very general way the larger top growths are accompanied by somewhat larger root growths, but because the correlation is so general, only the weight of the tops is considered in determining the minimum needs of the plant.

Oats are generally considered as having a low total potassium requirement and yet the maintenance of a concentration of 2 p.p.m. of potassium seems to be essential for the best growth. Increasing the concentrations up to 50 p.p.m. of potassium did not cause any additional growth. Very good growth was obtained at low concentrations. A concentration of only 0.5 p.p.m. of potassium produced two-thirds as much growth as the best concentration of 2 p.p.m.

ALFALFA AND HUBAM CLOVER

Alfalfa and Hubam clover are both regarded as needing large amounts of potassium for normal growth and for that reason will be discussed together. The alfalfa had grown 59 days in the nutrient solutions when it was harvested and the Hubam clover had grown 56 days. The oven-dry weights are given in table 1. As in the case of oats, the correlation between the weights of tops and roots of alfalfa is so general that only the weights of the tops will be considered in determining the minimum requirement of alfalfa for potassium.

Both alfalfa and Hubam clover seem able to make maximum growth if a concentration of 0.5 p.p.m. of soluble potassium is maintained. An increase in the concentration of soluble potassium up to 5 p.p.m. did not produce any larger amount of dry matter. The ability of these two crops to make such good growth on such a low concentration of potassium in contrast to the large amounts usually found in alfalfa and Hubam clover hay suggests that these crops may have great ability to feed upon the relatively insoluble soil minerals. That these plants can feed readily upon relatively insoluble potassium containing minerals such as feldspars has already been demonstrated by Bauer (4).

COWPEAS

The growth of cowpeas was very luxuriant, and marked evidence of physiological disturbances was only found in the plants receiving no potassium in their nutrient solution. The leaves turned to a purplish brown color about two weeks after these plants were transferred to the culture solutions, and made very little additional growth by the time of harvesting. The cowpeas were grown in the nutrient solutions for 38 days after which they were harvested. The results are given in table 1.

As in the preceding experiments, because of the very general correlation between the weights of tops and roots, only the dry weight of the top growth will be considered in determining the potassium requirement of cowpeas.

Cowpeas, according to the analyses given by Henry and Morrison (12), have a much higher total requirement for potassium than does alfalfa. In contrast to alfalfa, which was able to make its maximum growth on a concentration of 0.5 p.p.m. of potassium, the minimum concentration of potassium necessary to produce best growth of cowpeas appears to be very close to 2 p.p.m. This suggests a very marked difference in their ability to feed upon relatively insoluble potassium compounds and indicates that cowpeas, although having a

relatively high total potassium requirement, are unable to secure their minimum needs from very dilute solutions of potassium. However, very good growth was obtained at a concentration of 0.5 p.p.m. of potassium. In fact from the growth of the plants (pl. 1, fig. 1) it was practically impossible to see much difference in the plants growing in concentrations of from 1 to 5 p.p.m. of potassium. Part of the increase in weight of the plants growing in the solutions having a concentration of 5 p.p.m. of potassium was due to an extra 48 hours growth for special observations in connection with work of another problem.

SOYBEANS

The increasing importance of soybeans as a soil building and hay crop makes desirable some information in regard to its potassium requirement. For this reason soybeans were included in the crops studied. The technique used in growing these plants was the same as that described for the preceding crops. The plants started growing rather slowly after being transferred to the culture solutions, but after about a week they apparently recovered and made good growth. Forty-eight days after being transferred to the culture solutions the plants were harvested. The yields are given in table 1.

From the analyses given by Henry and Morrison (12) soybeans do not require nearly as much total potassium for best growth as do cowpeas and yet the maintenance of a concentration of approximately 2 p.p.m. of potassium was necessary for the production of best plant growth. Although a little more growth was produced at a concentration of 5 p.p.m. of potassium, it was considered due to plant variation, because the dry weights from concentrations of 2 and 3 p.p.m. of potassium were approximately the same. As with preceding crops, fairly good growth was obtained at a concentration of 0.5 p.p.m. of potassium without any indication of physiological disturbances which might be attributed to a deficiency of potassium.

SUDAN GRASS

Since Sudan grass does not have a very high potassium requirement, a comparison of it with crops such as alfalfa and cowpeas, which have high potassium requirements, may be of some value in studying the minimum concentrations necessary to produce good growth of different crops. Twelve plants per treatment were grown, in order to eliminate as far as possible differences in yields due to plant variations. The plants were very vigorous and made rapid growth after being transplanted to the culture solutions. After 38 days, pictures were taken of the plants and they were harvested. The results are given in table 1.

As probably might be expected, the correlation between dry weight of tops and roots was very general. On the whole it may be said that a large increase in dry weight of tops was usually accompanied by an increase in the dry weight of the roots.

From the dry weights of the tops, Sudan grass seems to require the maintenance of a higher concentration of potassium than do any of the preceding crops. The maintenance of a concentration of close to 3 p.p.m. of potassium seems to be necessary for the best growth of Sudan grass. However, good growth was obtained (pl. 1, fig. 2) in all solutions to which potassium had been added. The stems were very rigid and did not need any support to prevent breaking of the plants. About two-thirds as much growth was made with a concentration of 0.5 p.p.m. potassium as was obtained at the best concentration, namely, 3 p.p.m. of potassium. No evidence of any physiological disturbance such as might be caused by a deficiency of potassium was observed. The failure of 2 p.p.m. of potassium to produce any more growth than 0.5 p.p.m may be due to some extent to plant variation.

COTTON

More fertilizer is used on cotton than on any other crop, and a knowledge of its potassium requirement would give a better understanding for proper fertilization. The cotton plants, Trice 323, were grown as in the preceding experiments. They started growing rather slowly, after being transferred to the culture solutions, but after three weeks began to grow at what might approximate average rate of growth in the field. At the end of 81 days the plants were harvested. The dry weights are given in table 1.

The results indicate that the requirement of cotton is similar to that for cowpeas and that the maintenance of a concentration of potassium of approximately 2 p.p.m. is necessary for best growth.

This is rather interesting when it is considered that cotton has a relatively low potassium requirement as compared to cowpeas, and it may be one of the reasons why cotton responds so readily to applications of fertilizers. The growth at a concentration of 0.5 p.p.m. was not as good in proportion to that obtained from the higher concentrations as was found with the preceding crops.

POTASSIUM CONTENT OF PLANTS

It has been reported from a number of sources that plants seem able to take up more potassium than is actually needed for growth. One of the writers (2) has reported results that indicate a large consumption of potassium by alfalfa, oats, and Sudan grass above their actual needs. Blair (5) states that certain crops such as soybeans are able to take up an excess of potassium when there is an abundant supply. Lende (19) reports that plants will take up more potassium than they need for growth. If all plants will take up more potassium than needed for normal growth, it will not only put a new interpretation upon potassium fertilization but may be of value in helping to explain the ability of different plants to feed upon potassium compounds.

Analyses of potassium content were made on the plant tissue, as follows:

Weighed samples of plant tissue were saturated with H_2SO_4 and ignited.

The ash was extracted with water and made to a definite volume. Aliquots were evaporated to dryness with a little H_2SO_4 and then ignited. After cooling, a few cubic centimeters of water was added and the silica and iron were removed by filtration. The sulfates and any remaining iron and aluminum were removed with barium hydroxide. The barium was then removed by the addition of carbon dioxide and then filtering. Platinic chloride was added to the filtrate and the potassium weighed as potassium platinic chloride. The results of the analyses are given in table 2. The potassium content of the oat tops at a concentration of 10, 25, and 50 p.p.m. of potassium was 1.96 per cent, 3.52 per cent, and 3.33 per cent respectively.

As a general rule there was a gradual increase in the percentage of the potassium in the plant when the concentration of the potassium increased. The most noteworthy exception was the Hubam clover where the potassium content of the plants was approximately the same for plants grown in solutions containing 1, 2, 3, and 5 p.p.m. of potassium. Even in this case, however, there

TABLE 2

Percentages of potassium in plant tissues grown in nutrient solutions with concentrations of potassium indicated

K IN SOLUTION	K IN OATS TOPS	K IN ALFALFA TOPS	K IN HUBAM CLOVER TOPS	K IN COWPEAS TOPS	K IN SOY-BEANS TOPS	K IN SUDAN GRASS TOPS	K IN COTTON TOPS
p.p.m.	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
0.0	.....	.....	1.01	0.31	.....	0.40	0.78
0.5	1.22	1.76	1.76	0.71	1.13	0.52	0.81
1.0	1.34	1.54	2.67	0.81	1.63	0.68	1.18
2.0	2.40	2.17	2.58	1.08	1.77	0.92	1.10
3.0	2.61	1.90	2.71	1.20	2.21	0.84	1.48
5.0	3.03	2.24	2.60	1.34	1.97	1.07	1.80

was 50 per cent more potassium in the plants grown in a concentration of 1 p.p.m. than there was in plants grown in a concentration of 0.5 p.p.m. potassium, which was the minimum amount necessary for best growth. With alfalfa, the plants grown in a concentration of 1 p.p.m. potassium had a smaller percentage of potassium than the plants grown in 0.5 p.p.m., which was the minimum concentration necessary for best growth. All the other concentrations contained a considerably higher percentage of potassium. Cowpea, soybean, Sudan grass, cotton, and oat plants grown on concentrations of potassium greater than that required for normal growth, with the exception of plants grown in a concentration of 10 p.p.m. of potassium, all contained a considerably higher percentage of potassium than was found in the plants grown in the concentrations necessary for optimum growth.

The results of the analyses of Hubam clover and oats suggest that there is a maximum amount of potassium which plants will assimilate. In the case of Hubam clover the addition of potassium above a concentration of 1.0 p.p.m. failed to increase the percentage of potassium in the plant. With oats there

was an increase in potassium content of the plants up to a concentration of 25 p.p.m. of potassium in solution. Increasing the concentration to 50 p.p.m. of potassium had no effect upon the percentage of potassium in the plant. The assimilation of available potassium in amounts equivalent to the maximum capacity of plants would play a very important part in determining the residual effects which could be expected from applications of potassium fertilizers. However, the results are only suggestive and further study is necessary to determine whether all plants have a maximum capacity for the assimilation of potassium.

GENERAL DISCUSSION

The results of the experiments have shown that there is a decided difference in the concentrations of potassium necessary to produce best growth. Alfalfa and Hubam clover required the maintenance of a concentration of only 0.5 p.p.m. of potassium to make best growth, whereas cowpeas, oats, soybeans, and cotton required the maintenance of a concentration of 2 p.p.m. for the most favorable growth. To produce the best yield, Sudan grass required the maintenance of a higher concentration than any of the above crops—3 p.p.m.

There was no correlation between the total potassium requirements of the plants and the minimum concentration which must be maintained to secure best growth. For example, cowpeas, alfalfa, and Hubam clover are regarded as crops requiring large total amounts of potassium for normal growth and yet a concentration of only 0.5 p.p.m. was sufficient, when maintained, to completely satisfy the needs of the latter two crops, whereas the maintenance of a concentration of 2 p.p.m. of potassium was essential for the best growth of cowpeas. Soybeans with a moderate total requirement for potassium, and oats with a relatively low total potassium requirement both need the maintenance of a concentration of 2 p.p.m. of potassium in order to make the best growth. On the other hand, Sudan grass, which is regarded as having a low total potassium requirement, needed the maintenance of approximately 3 p.p.m. of potassium for best growth.

The differences in the concentrations of potassium necessary to produce best growth of plants may offer some explanation for the differences in the ability of plants to produce good growth from difficultly soluble potassium compounds. The results of these studies suggest that both alfalfa and Hubam clover should be able to feed very heavily upon slightly soluble potassium minerals such as orthoclase feldspar. This is in excellent agreement with results presented by Bauer (4), who secured normal growth of sweet clover when feldspar was the only source of potassium. On the other hand oats, cowpeas, soybeans, cotton, and Sudan grass would not be expected to feed very heavily upon relatively insoluble potassium minerals because they require much larger concentrations for best growth.

The cause of the difference in potassium requirements of the plants could not be determined from these experiments. Part of it might be explained from

the theory advanced by Truog (28), that variations in the internal acidity of the plants greatly affect the ability of the plant to feed upon potassium. According to his theory, plants, such as alfalfa and sweet clover, whose sap has a slightly acid to alkaline reaction should do very well upon small concentrations of potassium while other crops having a more acid sap would require greater concentrations of potassium for normal growth. It is doubtful, however, whether the foregoing explanation would account for the intake of potassium above the amount necessary for minimum growth. More work is necessary to determine the cause of the assimilation of excessive amounts of potassium by plants and the action, if any, of the excess of potassium in the plant.

In all of the experiments good growth was obtained at a concentration of approximately 0.5 p.p.m. of potassium, and no evidence of physiological disturbances due to a deficiency of potassium was observed. Apparently the symptoms supposedly characteristic of potassium starvation develop only when the concentration of soluble potassium is extremely small.

Data, to be published in the near future, from studies with tomato plants show that the potassium in the plants is very labile. In other words, if there is a deficiency of potassium for normal growth in an embryonic region, sufficient potassium will be translocated from a region of older tissue to permit the plant to function almost normally in the embryonic region. When the deficiency of available potassium becomes very great, however, physiological disturbances will be observed in the older regions.

From a consideration of the foregoing facts, it seems reasonable to believe that when physiological disturbances which may be attributed to a deficiency of potassium are observed in the embryonic regions, the amount of potassium available for plant growth is practically nil.

The assimilation of large amounts of potassium by plants from solutions of greater concentration than that required for maximum growth will enable plants, because of the lability of the potassium assimilated, to function normally when the concentration in solution is reduced below that essential for best growth.

The ability of plants to take up excessive amounts of potassium may determine to a great extent the residual effect which may be expected from the application of a potassium fertilizer. If the potassium remains fairly available after being applied to the soil, most of that added in the fertilizer may be removed by the first crop and the residual affect may be rather small, if any.

From the standpoint of fertilizer practices it would appear to be almost necessary to make approximately the same application of potassium fertilizers for all crops. Although many of the crops may not use all of the potassium added, the larger application seems to be essential to maintain a concentration large enough to secure best growth of those requiring a concentration of approximately 2 to 3 p.p.m. of potassium.

SUMMARY

In order to determine the minimum concentration of potassium which is necessary to produce optimum growth, oats, alfalfa, Hubam clover, cowpeas, soybeans, Sudan grass, and cotton were grown in culture solutions having different concentrations of potassium. Analyses were made on the plant tissue to determine whether plants have the ability to assimilate more potassium than that required for optimum growth. The results of the experiments may be briefly summarized as follows:

1. There was considerable variation in the requirements of different plants. Alfalfa and Hubam clover were able to make optimum growth in a solution containing 0.5 p.p.m. of potassium. Oats, cowpeas, soybeans, and cotton made best growth at a concentration of 2 p.p.m. potassium while Sudan grass required a concentration of 3 p.p.m. in order to produce the best growth.
2. All the plants made good growth at a concentration of 0.5 p.p.m. potassium.
3. There was no relation between total potassium requirements of plants and the concentration necessary to produce optimum growth. For example, oats and cowpeas have a low and high total potassium requirement respectively, and yet both needed a concentration of 2 p.p.m. of potassium to make optimum growth.
4. Plants absorbed more potassium than is required for optimum growth.

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PLATE 1

FIG. 1. Growth of cowpeas in nutrient solution with parts per million of potassium indicated.

FIG. 2. Growth of Sudan grass in nutrient solution with parts per million of potassium indicated.

FIG. 1

FIG. 2

A CRITICAL STUDY OF THE INFLUENCE OF SOIL TYPE ON THE CALCIUM AND MAGNESIUM CONTENT AND OTHER PHYSIOLOGICAL CHARACTERS OF THE ALFALFA PLANT[1]

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Alfalfa is so important in the rations of all classes of farm animals, and its use in the maintenance and improvement of soil fertility has become so extensive that some knowledge, both of the degree to which its composition is variable and of the effect of soil differences upon its composition, is of unquestioned value.

Up to the present time considerable work has shown that a number of plants vary in composition when grown under different soil conditions and when given different fertilizer treatments. One of the important phases of this work has been in connection with the effect of different soil conditions upon the composition of the expressed juice of the plants.

It was to obtain information of the foregoing nature, in regard not only to the alfalfa plant but to several of the other important legumes, that this study was undertaken. This paper includes data showing the variations in the calcium and magnesium content of alfalfa stems and leaves, and likewise of their expressed juices, at different ages when grown on different soil types. In addition to these it contains data bearing on other relationships of the alfalfa plant and soil type.

HISTORICAL

McCool (14) has shown that the addition of fertilizers to soils under field conditions causes a measurable increase in the concentration of the expressed sap of corn plants, of sugar beets, of table beets, and of onions, and to a less extent of table carrots. These data also showed that there was nearly as much variation among the concentrations of the sap of young corn plants grown on different soil types, as there was among those grown on fertilized and unfertilized plots. The addition of fertilizers as noted by Austin (2) altered the composition of soybeans. The greatest effect was on Coloma sand and the least on Miami loam. But it was also observed that soil type was of greater

[1] A part of a thesis presented to the graduate committee of the Michigan State College in partial fulfillment of the requirements for the degree of doctor of philosophy.

[2] The writer wishes to express his appreciation to Dr. M. M. McCool for his kindly interest in helping to plan and organize the work presented here.

influence in determining the composition of the soybean plants than was the application of fertilizers. McCool and Weldon (16) observed that the addition of fertilizers caused no evident increase in the amounts of calcium and magnesium present in the juice of wheat grown on Hillsdale sandy loam, but that the application of lime alone gave greater amounts of calcium present in the expressed juice. It was concluded by these authors that the application of the various nutrients to the soil generally resulted in an increase of these elements in the plant juice. Experiments carried out by Morse (19) seem to indicate less CaO in the plant tissue of clover, on a dry basis, grown on limed soils than on unlimed. On the other hand, Bryan (3) found that the calcium content of the tissue of alfalfa, alsike clover, and red clover grown in sand cultures was higher when the reaction of the nutrient solution was higher. McCool (15), states that the composition of the roots and tops of alfalfa varies according to soil fertility, stage of development, and varieties grown. It was concluded by Gilbert and Hardin (7) that the amounts of mineral elements in plant solutions were closely correlated with the amounts of these added in fertilizers.

Dinsmore (6) found, as alfalfa advanced in growth, a rather wide fluctuation in total ash content, although the tendency was to decrease as the plants became more mature. This was borne out by Widstoe (23), who showed also that there was a greater amount of water in the stems than in the leaves of alfalfai n the early stages of growth but that as the plants become older it was nearly the same in the stems and leaves or even greater in the leaves. The dry matter was greater in the leaves in the beginning but toward maturity became much less than in the stems. In second cutting alfalfa, the ash content was found by Widstoe (23) to be lower than that of the first cutting. Austin (2) found the calcium and magnesium content of soybeans to decrease as the plants became older and that the magnesium content was not so uniform as the calcium content. Burd (4) showed that in barley there were probably three periods of growth: one, a preliminary period of about six weeks in which the greatest gain in weight occurred; then a period of about six weeks in which the rate of gain in total weight became negligible; and a third period, continuing until maturity, in which there was an actual loss in weight, not only in the whole plant but in the various parts as well. However, it was observed further that the increase in dry matter followed a fairly straight line throughout the life of the plant and that the increase of calcium and magnesium parallel the formation of dry matter up to the eighth or ninth week, when the increase of these two elements lags behind. There was a decrease in calcium and magnesium in both the stems and the leaves at the time the heads were forming. This last result corroborated the findings of Hornberger (12). Russel (20) notes that magnesium, like phosphorus, finally moves to the seed, and is thus in contrast with calcium and potassium which remain behind in the leaf and straw. According to Hoagland (11) marked absorption of all the nutrient elements in sand and water cultures took place at all periods up to

the final stage of growth. Whiting and Richmond (22) report that the calcium and magnesium content of the tops of the sweet clover plant changed but little during the first season's growth and that there was a ratio of about 3:1 for these elements. However, during the second season's growth the calcium and magnesium content decreased noticeably, there being one-third as much present at the end of the period of growth as at the beginning.

Widstoe (23) gave data to show the proportions of stem to leaves throughout the growing period of alfalfa. In the beginning there was a greater proportion of stems than of leaves—the amounts being 71.48 per cent stems and 28.52 per cent leaves. At maturity the proportion had changed to 35.83 per cent stems, 57.23 per cent leaves, and 6.94 per cent blooms. In the second cutting the proportions at the time buds were beginning to form was 51.03 per cent stems and 48.97 per cent leaves, and at maturity 30.51 per cent stems and 67.02 per cent leaves. Widstoe decided that alfalfa did not start to bloom until the leaves and stems were present in nearly like proportions, varying between 50 to 60 per cent of stalks and 40 to 50 per cent of leaves.

PLAN OF EXPERIMENT

The fundamental object of the work undertaken here was to determine what variations may occur in the composition of alfalfa plants grown on different soil types. The deep rooting habit of the alfalfa plant encourages the expectation that soil types do not greatly influence the composition of the plants. Millar (18) showed that the roots of alfalfa are able to obtain food from the substrata if the materials there are available. If alfalfa plants are able to obtain the mineral elements from any portion of the soil profile where the supply is abundant, there should be little variation in the composition of plants grown on different soil types because of the feeding range.

The results here reported are based on studies which were conducted during the growing season of 1928, beginning as soon as alfalfa had attained sufficient size for sampling. The first samples were taken on May 8 and thereafter at two-week intervals until June 7. After this date samples were collected when the plants had reached fall bloom, the date of which varied considerably on the different soil types. The samples taken on June 7 were just beginning to show buds. Three samples were obtained from the second growth of alfalfa, the first being taken on July 24 and the last at the full bloom stage. Thus the data obtained would not only show variations due to soil type, but would also give the variations at different stages of growth. Separate analyses were made of the leaves and stems and of the expressed juice of leaves and stems.

Alfalfa growing on the following soil types was used: Coloma loamy sand, Plainfield loamy sand, Hillsdale sandy loam, Fox sandy loam, Conover loam, Brookston loam (heavy), and Miami silt loam.

The alfalfa used in this study was of the Grimm variety, all the fields being located in Ingham County, five of them within 12 miles of East Lansing and

the remaining two, on Brookston and Fox soil, at distances of 17 and 25 miles respectively.

EXPERIMENTAL PROCEDURE

All alfalfa samples were gathered between 8 and 10 a.m. on clear days, as McCool and Millar (17) had found that the freezing point lowerings indicated variations in the plant material at different hours of the day. The samples were placed immediately in a saturated atmosphere and brought to the laboratory in this condition.

As soon as possible after getting the samples to the laboratory, the leaves and stems were separated and 10-gm. samples of each were weighed out for total analysis and moisture determination. The remaining material was pressed to furnish the juice for analysis.

The juice was expressed from all samples at seven tons pressure per square inch, a constant pressure being necessary, as previous workers (8, 10, 13, 17) have shown that the concentration of the expressed juice varies according to the pressure applied and the previous treatment of the plant material. The specific gravity of the juice was determined and portions of about 10 gm. were then weighed out into porcelain crucibles for ashing. The juice thus obtained, along with the plant material weighed out as stated before, was ashed in a muffle furnace at dull red heat, taken up in five normal hydrochloric acid, and made up to 100 cc. The calcium determinations were made by the usual official volumetric method, 25-cc. aliquots being used for each determination. Twentieth normal K MnO_4 was used to permit greater accuracy, and all results reported are averages of closely agreeing duplicates. The magnesium determinations were made by the volumetric method of Handy (9); the filtrates from the calcium determinations being carefully obtained for this purpose. Twentieth normal KOH was used as the alkali and the averages of closely agreeing duplicates only are reported in this paper. No difficulties were experienced in these determinations as long as the described methods were adhered to and great care was observed in washing and drying filtrates.

EXPERIMENTAL RESULTS

Calcium content of first growth alfalfa stems and leaves

Calcium is such an important element in animal metabolism and its deficiency in a ration is followed by such objectionable effects that some knowledge of the variations which may occur in the calcium content of alfalfa is desirable, especially in the compounding of rations for poultry and swine.

The calcium content of alfalfa stems grown on different soil types and analyzed at different growth stages is given in table 1. According to these data there was a noticeable and consistent variation in the calcium content of the alfalfa grown on the different soil types throughout the growth period. More calcium was found in the stems of plants taken from the heavy soil

types than from the lighter types at each stage of growth except that of full bloom, July 2, where the calcium content dropped on Brookston and Miami soils. The loam soils, Hillsdale and Fox, gave stems with the highest calcium content throughout the period of growth.

Generally a higher percentage of calcium was present in the stems at maturity than at the early stage of growth and the increase was quite uniform on all the types. With the exception of the stems of the plants grown on Coloma loamy sand, a decrease in the calcium content occurred after the plants reached the budding stage, or on June 7, and this decrease was greater in the stems obtained from the very heavy soils.

The calcium content of alfalfa leaves as percentage of dry material is also given in table 1. Much greater variation was evident in the amounts of calcium

TABLE 1

Calcium content of first growth alfalfa stems and leaves at different stages of growth when grown on different soil types*

SOIL TYPE	STAGES OF GROWTH							
	Very young May 8		May 22		June 7		July 2	
	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Plainfield	0.770	1.103	0.777	0.826	0.782	2.140	0.767	2.522
Coloma	0.897	1.211	0.842	1.683	0.885	1.695	0.913	2.930
Hillsdale	0.850	1.182	1.051	2.120	1.025	2.339	0.911	4.060
Fox	0.956	1.571	0.993	1.737	1.172	3.108	1.167	4.020
Conover	0.949	1.353	.....	1.710	1.404	3.830	Not obtained	
Brookston	0.946	1.161	1.283	1.748	1.183	2.568	0.864	2.250
Miami	0.915	1.468	1.070	1.917	1.561	2.148	0.972	2.610

* Dry basis.

present in the leaves of alfalfa grown on different soil types than was found for alfalfa stems.

Throughout the period of growth, the calcium content was highest in the leaves grown on the soils of medium texture as compared with the very light or the very heavy soils.

The calcium content of alfalfa leaves increased uniformly as the plants became older and the percentage of calcium at full bloom was from two to nearly four times as great as in the very young leaves. The leaves grown on Brookston loam soil were the only ones to show a decrease in calcium after the budding stage, and the increase in the leaves obtained from Miami soil was small. These facts, and those noted in the case of the stems where the decrease after the budding stage was greater on these two heavy soils, may be explained by the fact that in these plants there was an adjustment made between the calcium present and some other cation as potassium, which did not occur in the plants obtained from the lighter soils.

The calcium content of alfalfa leaves was greater than that found for stems of the same plants. In the very young plants, this difference in calcium content of the leaves and stems was slight, but at maturity it was much greater, there being nearly four times as much calcium in the leaves as in the stems.

The data on the percentage of calcium present in the expressed juice of alfalfa stems grown on different soil types are given in table 2. It is apparent that there were differences in the calcium content of the juice obtained from stems of plants grown on the different soil types, although they are not consistent throughout the growing period. Generally the calcium content was low in the juice of stems grown on the very sandy soils and high on the sandy loams and the loams.

TABLE 2

Calcium content of expressed juice of first growth alfalfa stems and leaves at different stages of growth on different soil types

SOIL TYPE	STAGE OF GROWTH							
	May 8		May 22		June 7		July 2	
	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Plainfield	0.133	0.175	0.060	0.185	.....	0.332	0.074	0.389
Coloma	0.133	0.275	0.068	0.227	0.095	0.262	0.145	0.618
Hillsdale	0.086	0.247	0.088	0.287	0.106	0.415	0.177	0.754
Fox	0.111	0.219	0.092	0.316	0.144	0.564	0.154	0.903
Conover	0.123	0.237	0.082	0.240	0.193	0.623	Not obtained	
Brookston	0.147	0.244	0.133	0.297	0.167	0.439	0.125	0.408
Miami	0.092	0.210	0.104	0.255	0.165	0.502	0.196	0.713

Although no uniform increase occurred in the percentage of calcium in the juice of alfalfa stems, there was a general tendency for the concentration to be higher in the juice of the mature stems than in that of the young stems. The plants obtained from Plainfield and Brookston soils were the only exceptions. The plants obtained from Brookston soil likewise were the only ones which showed a depression of calcium in the expressed juice of the stems after the budding stage, due again perhaps to the balance between the cations noted before. The period of greatest depression occurred on all of the soil types, with the exception of Hillsdale and Miami soils, at the time the second sampling was made (May 22). Although these exceptions cannot be explained, this depression at this time was probably due to a greater moisture content in the stems, a fact which will be brought out in subsequent data.

The calcium content of the expressed juice of alfalfa leaves grown on different soil types is given in table 2, along with the similar data relative to the juice

of the stems. Large differences existed in the concentration of calcium in the juice obtained from leaves grown on different soil types, although the differences were not especially great in the juice of the young leaves.

The greatest concentrations of calcium appear to have been present in the juice of leaves grown on the heavy soil types, although that of the juice of leaves grown on Brookston loam was quite low. As usual, greater percentages of calcium were present in the juice of the leaves grown on Fox and Conover sandy loams than on either the very light or the very heavy soils.

A rather uniform increase in calcium content occurred in the juice of leaves as the plants became older and there does not appear to have been any stage of growth where a general depression occurred. However, the increase in concentration was small on May 22 on nearly all of the soil types and on some there was a depression of calcium in the juice of the leaves at this time. These

TABLE 3

Magnesium content of first growth alfalfa stems and leaves at different stages of growth on different soil types*

SOIL TYPE	STAGE OF GROWTH							
	May 8		May 22		June 27		July 2	
	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Plainfield	0.247	0.256	0.313	0.285	0.184	0.258	0.156	0.337
Coloma	0.268	0.224	0.256	0.309	0.228	0.199	0.220	0.321
Hillsdale	0.231	0.226	0.400	0.244	0.240	0.241	0.238	0.330
Fox	0.396	0.268	0.366	0.297	0.369	0.397	0.325	0.587
Conover	0.414	0.313	0.495	0.250	0.484	0.444	Not obtained	
Brookston	0.319	0.241	0.388	0.203	0.325	0.263	0.174	0.263
Miami	0.336	0.265	0.346	0.284	0.432	0.262	0.211	0.298

* Dry basis.

conditions were probably due to the greater moisture content of the leaves at this stage of growth. Without exception, the concentration of calcium was greater in the juice of mature leaves than in that of the young leaves.

The percentage of calcium in the expressed juice of alfalfa leaves was higher than that of the juice of alfalfa stems. In the young plants, the concentration of calcium in the juice of leaves was about twice as great as in the juice of stems, but as the plants became older the difference became greater until at maturity the concentration of calcium in the juice of the leaves was five or six times that in the juice of the stems.

About one-fifth as great a percentage of calcium was present throughout the period of growth in the juice of alfalfa leaves as in the tissue of leaves. The increase in concentration of calcium in the juice was accompanied by a similar increase of calcium in the tissue of the leaves.

Magnesium content of first growth alfalfa stems and leaves

Although probably of less importance than calcium from the nutritional standpoint, magnesium is an important constituent of all plant materials and a knowledge of variations in the amounts present in plants at different times in the growth period and as affected by soil type is undoubtedly valuable.

The magnesium content in percentage of dry material present in the stems of first growth alfalfa on different soil types is given in table 3. It is evident that throughout the growth period there was considerable difference in the amount of magnesium present in the stems grown on the various types of soil. During the entire growth period the heavier soil types gave stems containing noticeably greater amounts of magnesium than did the light soils, although as the plants became older this influence of soil texture became less marked. Higher magnesium content was always evident in the stems grown on the sandy loam soils, Fox and Conover, than in the stems grown on either the very heavy or the very light soils.

A depression of greater or less magnitude occurred in the magnesium content of stems grown on all of the soil types after the budding stage. On some of the soil types, as Coloma, Plainfield, and Brookston, the decrease of magnesium in the stems may be almost uniform from the early stage of growth to maturity. With but one exception the percentage of magnesium was lower in the mature stems than in the very young stems samples on May 8.

The magnesium content of alfalfa stems was much lower than the calcium content throughout the period of growth. Although the amount of magnesium varied very uniformly with that of calcium, it did not parallel the amount of the calcium, at times rising and falling independently of it.

Table 3 likewise contains data showing the magnesium content of first crop alfalfa leaves at several stages of growth on different soil types. Variations appeared in the percentages of magnesium in the leaves grown on the different soil types, but until the plants approached maturity the differences were not great. At no time during the period of growth could the influence of soil texture be discerned except insofar as the leaves from plants grown on Fox and Conover sandy loams were generally somewhat higher than those produced on the other soil types. Usually the magnesium content was as high in the leaves grown on sandy soils as that of the leaves obtained from heavy soils.

The amount of magnesium increased in the leaves of alfalfa on all the types as the period of growth advanced. This increase was more evident in the leaves grown on loamy sands and sandy loams than in those grown on the heavier loam soils, and on only one type was this increase uniform from first to last. Thus periods of depression were noted on all soil types except Fox sandy loam at one or another of the periods of sampling.

The magnesium content of alfalfa leaves was about equal to that of alfalfa stems at each stage of growth on all the soil types. A deviation from this

occurred at the mature stage when the percentage of magnesium in the leaves became greater than that in the stems, partly by because of the increase in the leaves after the budding stage and partly because of the decrease or depression noted in the stems at the same time.

The magnesium content of alfalfa leaves was always much lower than the calcium content. The proportion of magnesium to calcium was about 1:5 in the very young plants and increased to about 1:8 at maturity. This increase in the magnesium-calcium ratio was not noted for stems; the ratio remaining about 1:4 throughout the entire growth period.

Table 4 shows the percentages of magnesium present in the expressed juice of first growth alfalfa stems grown on different soil types. The influence of soil type was evident throughout the growing period of the plant, but at no stage of growth was there any evidence that the texture of the soil was related

TABLE 4

Magnesium content of expressed juice of first growth alfalfa stems and leaves at different stages of growth on different soil types

SOIL TYPE	STAGE OF GROWTH							
	May 8		May 22		June 7		July 2	
	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Plainfield	0.084	0.075	0.038	0.038	0.026	0.052	0.045	0.076
Coloma	0.053	0.079	0.038	0.043	0.036	.....	0.068	0.096
Hillsdale	0.038	0.056	0.045	0.052	0.050	.....	0.067	0.088
Fox	0.047	0.060	0.052	0.064	0.048	0.072	0.081	0.115
Conover	0.034	0.053	0.055	0.064	0.076	0.076	.....	.....
Brookston	0.064	0.078	0.060	0.052	0.060	0.062	0.052	0.067
Miami	0.041	0.051	0.052	0.050	0.062	0.062	0.084	0.088

to the concentration of magnesium in the juice of the stems except the fact that at the two intermediate growth stages the concentration was least in the stems grown on Plainfield and Coloma loamy sands.

Except on Plainfield loamy sand and Brookston loam, the concentration of magnesium in the juice of alfalfa stems was greater at maturity than at the early part of the growth period. On some of the types, as Hillsdale sandy loam, Conover sandy loam, and Miami silt loam, the increase in the concentration of the juice of stems was uniform from first to last; on the other types there was a depression in the amount of magnesium present in the juice of the stems at one of the stages of growth succeeding the first.

There was a smaller amount of magnesium in the juice of alfalfa stems than there was calcium and the ratio remained about 1:2 or 1:3 throughout the period of growth. The soil type which gave a high calcium content in the juice of stems likewise gave a high magnesium content, and the fluctuations

during the growing period occurred somewhat nearly at the same time for both calcium and magnesium.

The magnesium content of the juice of alfalfa leaves grown on the different soils is also given in table 4. That variations in the concentration of the juice of leaves grown on different soil types occurred, is quite evident and they continued throughout the growth of the plant. In the very young plants there appeared to be no influence of soil texture but as the plants became older those grown on the heavy soils, and especially those grown on the sandy loams, showed a higher magnesium content in the juice of their leaves than did those grown on the light sandy soils. At the stage of full bloom little effect of soil texture on the magnesium content of the juice was evident. At this time Fox sandy loam gave leaves with a considerably greater amount of magnesium in

TABLE 5

Calcium content of second growth alfalfa stems and leaves at different stage of growth on different soil types*

SOIL TYPE	STAGE OF GROWTH					
	July 24		August 7		Full bloom	
	Stems	Leaves	Stems	Leaves	Stems	Leaves
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Plainfield	1.198	1.289	1.261	1.598	.....	.....
Coloma	1.170	.....	1.044	1.895	1.092	3.690
Hillsdale	1.125	1.618	1.038	2.080	1.060	2.19†
Fox	2.047	1.787	1.047	2.065	0.932	2.550
Conover	1.410	2.020	1.249	2.388	0.900	3.955
Brookston	1.337	1.874	1.158	3.432	0.991	2.680
Miami	1.347	1.792	.....	.....	0.864	2.950

* Dry basis.

† Half bloom.

their juice than did any others, and the sandy soils were about equal to the heavy soils in this respect.

Greater amounts of magnesium were present in the juice of mature alfalfa leaves than in immature ones, though the difference was very small. On all of the soil types studied, except the sandy loams, there was a depression in the concentration of magnesium in the juice of alfalfa leaves on May 22. This depression, which corresponds to the depression noted for the calcium content at this stage of growth, was most noticeable on the sandy soils.

The magnesium content of the juice of alfalfa leaves was but slightly higher at any time than that of the stem juice. The relative concentrations remained about the same during the growing period so that at no time was the concentration of the juice of one much different from that of the other.

Much smaller amounts of magnesium than of calcium were present in the juice of first growth alfalfa leaves. The proportion of magnesium to calcium

was less in the young plants, about 1:4, but increased as the plants become older until it was about 1:7, or even wider.

Calcium and magnesium content of second growth alfalfa stems and leaves and in their expressed juices

The analysis of second growth alfalfa showed that the calcium and magnesium contents of the tissue and of the juice of both stems and leaves corresponded quite closely to those found in the first crop. Some disagreements were found, however, which are worthy of note.

More calcium was present throughout the growth period, and a more rapid and more general decrease occurred in the percentage of calcium, as the period of growth advanced, in the second crop stems (table 5) than in the first crop stems.

TABLE 6

Calcium content of expressed juice of second growth alfalfa stems and leaves at different stages of growth on different soil types

SOIL TYPE	STAGE OF GROWTH					
	July 24		August 7		Full bloom	
	Stems	Leaves	Stems	Leaves	Stems	Leaves
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Plainfield	0.104	0.204	0.075	0.198	.....	.....
Coloma	0.122	0.174	0.084	0.243	0.202	0.892
Hillsdale	0.106	0.200	0.094	0.280	0.108	0.364*
Fox	0.106	0.247	0.112	0.345	0.168	0.668
Conover	0.134	0.295	0.127	0.403	.....	.....
Brookston	0.128	0.290	0.130	0.430	0.170	0.678
Miami	0.115	0.245	.....	.....	0.157	0.708

* Half bloom.

Greater amounts of calcium appeared in the leaves of the second crop (table 5) when the plants were young than occurred in those of the first crop, but the increase of calcium from early growth to maturity was slower in the second growth leaves, resulting in a lower content at full bloom than was observed in the first crop leaves. The least increase of calcium with advancing age occurred in the leaves of plants obtained from the soil types which had given up the greatest amounts of calcium to the first crop.

From table 6 it is evident that similar amounts of calcium were present in the expressed juice of both stems and leaves of the two crops throughout the growing period.

Soil type produced variations in the calcium content of the second crop which were similar in magnitude to those produced in the first crop but the influence of soil texture was much less evident and became practically negligible

toward the close of the growth period, perhaps because of an equalizing of the supply of calcium in the nutrient medium.

Tables 7 and 8 show that only the following differences occurred in the magnesium content of the second crop in comparison with that of the first crop of alfalfa.

TABLE 7

Magnesium content of second growth alfalfa stems and leaves at different stages of growth on different soil types*

SOIL TYPES (INCREASING TEXTURES)	DATE OF SAMPLING					
	July 24		August 7		Full bloom	
	Stems	Leaves	Stems	Leaves	Stems	Leaves
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Plainfield	.....	0.446	0.300	0.374	.....	.....
Coloma	0.690	.....	0.322	0.311	0.408	0.489
Hillsdale	0.578	0.583	0.292	0.490	0.348	0.393†
Fox	0.648	0.535	0.184	0.310	0.310	0.366
Conover	0.760	0.539	0.537	0.502	0.501	0.741
Brookston	0.537	0.523	0.351	0.381	0.246	0.381
Miami	0.798	0.470	.....	.....	0.360	0.489

* Dry basis.

† Half bloom.

TABLE 8

Magnesium content of expressed juice of second growth alfalfa stems and leaves at different stages of growth on different soil types

SOIL TYPES (INCREASING TEXTURES)	DATE OF SAMPLING					
	July 24		August 7		Full bloom	
	Stems	Leaves	Stems	Leaves	Stems	Leaves
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Plainfield	0.093	0.088	0.048	0.072	.....	.....
Coloma	0.079	0.081	0.045	0.064	0.129	0.134
Hillsdale	0.088	0.088	0.069	0.088	0.076	0.086*
Fox	0.084	0.096	0.048	0.074	0.084	0.122
Conover	0.112	0.105	0.105	0.093	.....	.....
Brookston	0.096	0.091	0.086	0.098	0.103	0.110
Miami	0.100	0.084	.....	.....	.....	0.144

* Half bloom.

Greater amounts of magnesium were present in the tissue and in the juice of both stems and leaves of the second growth than occurred in the first growth.

A more rapid decrease took place in the magnesium content of the tissue of second growth stems than in that of the first growth stems as the period of

growth advanced. In the juice of the stems of the second crop a smaller increase of concentration of magnesium occurred than was found in the juice of the first growth stems.

A tendency was apparent for the magnesium content of the tissue of second crop leaves to decrease with advancing age in contrast to the general tendency for it to increase in the tissue of first growth leaves.

Soil texture was less marked in its influence upon the magnesium content of the second crop of alfalfa than upon that of the first crop. In the second growth the Fox soil appeared to have lost its ability to produce alfalfa containing the large amounts of calcium and magnesium which were observed in the plants obtained from that soil during the first growth period.

Calcium and magnesium content of the plant tissue of alfalfa stems and leaves free of all sap

The quantity of any substance found in moisture-free plant tissue consists of the amount of this substance present in the woody tissue plus the amount originally present in the juice of the plant and left in the tissue upon drying. In order to determine the amount of any substance which makes up a part of the structural tissue of the plant it is necessary to separate from this the amount contained in the juice of the green plant material.

Attempts have been made by some workers (5, 20) to extract separately material of the vacuole portion of plant cells and the material contained in the protoplasm. The methods used were chemical, as the application of extreme mechanical methods was considered to break open the cell wall and allow the escape of some of the protoplasmic material.

In the work presented here the woody plant tissue is considered to consist of cell walls only. Any material in solution or suspension in the vacuole or protoplasmic material is not considered as incorporated in the structural tissue of the plant. Because of this, the total material expressed under rather high pressure, as seven tons per square inch, is assumed to represent the plant substance other than that of the woody tissue, although there is considerable controversy on this point among a number of workers (8, 9, 12).

If the amount of a substance present in the green material of the plant and the amount in the liquid portion of the plant material (represented here by the content in the expressed juice of the plant) are known, the amount of the substance in the woody tissue can be found as the difference of these two. This procedure is represented by the following equation for the determination of a substance *A:*

$$A \text{ in woody tissue} = \text{per cent } A \text{ in green plant material} - \text{per cent } A \text{ in juice} \times \text{grams juice per grams green material.}$$

The data necessary in the use of this equation consist of the percentage of the substance sought in the green tissue of the plant, the percentage of the substance in the expressed juice of the green material, and the exact moisture

content of the green material. The moisture content of the plant equals, with but slight error, the total amount of plant juice which could be extracted if it were possible to press the material so greatly that it would be moisture free.

Results obtained from the use of the above formula are incorporated in tables 9 to 12 inclusive. The moisture content of the materials is presented subsequently in table 13.

The amounts of calcium in the woody tissue of first growth alfalfa stems and leaves when the plants were very young and also when they were at full bloom are given in table 9. A much smaller amount of calcium was present in the woody tissue of young alfalfa stems than in that of old ones. This indicates that during the period of growth a certain amount of calcium was being added to the tissue. The amounts of calcium deposited in the tissue of the stems after the plants were sampled on May 8 until they were in full

TABLE 9

Relative amounts of calcium present in the woody tissue of first growth alfalfa stems and leaves in early growth and at maturity

When grown on different soil types

SOIL TYPE	EARLY STAGE, MAY 8				MATURE STAGE					
	Mgm. Ca per gm. green material		Mgm. Ca in tissue of 1 gm. green material		Mgm. in gm. green material		Mgm. Ca in tissue of 1 gm. green material		Amount added after May 8, mgm. per gm.	
	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
Plainfield	1.14	2.06	0.003	0.634	2.00	5.78	1.50	0.297	1.497	−0.337
Coloma	1.60	2.75	0.500	0.619	2.40	6.97	1.33	0.150	0.830	−0.469
Hillsdale	1.38	2.50	0.664	0.551	2.38	9.11	1.31	0.327	0.646	−0.224
Fox	1.56	3.47	0.627	0.177	2.56	9.76	1.21	0.294	0.583	0.117
Brookston	1.84	2.64	0.655	0.075	2.00	6.00	1.03	0.300	0.375	0.225
Miami	1.565	3.24	0.796	0.161	2.64	7.08	1.21	0.190	0.414	0.030

bloom varies from 0.375 mgm. per gram of green material to 1.49 mgm. per gram.

Widely different amounts of calcium were present in the woody tissue of first growth alfalfa stems grown on the different soil types. Stems grown on Plainfield soil contained in their woody tissue when very young, only 0.003 mgm. of calcium per gram, whereas those grown on Miami soil contained in their woody tissue 0.796 mgm. per gram. At maturity the stems grown on Plainfield soil contained 1.50 mgm. calcium per gram in their woody tissue and those grown on Brookston soil contained only 1.03 mgm. per gram. Consequently it appears that the texture of the soil influenced the amount of calcium deposited in the woody tissue, that of stems grown on heavy soil types containing more calcium when very young than that of stems grown on light soils, and the woody tissue of stems grown on heavy soils containing less at full bloom than that of stems grown on light soils.

There was a much greater amount of calcium deposited in the woody tissue of stems grown on the sandy soils during the period of growth following the first sampling. These data indicate that at no time during the period of growth was calcium actually removed from the woody tissue of the stems, as may have been interpreted from the analysis of the dry material (table 1).

The data in table 9 show that noticeable differences existed in the amounts of calcium deposited in the woody tissue of the first growth leaves from the different soil types both in the early stage of growth and at full bloom. Greater amounts of calcium were present in the woody tissue of the leaves grown on heavy soils when the leaves were young. As the period of growth advanced, however, calcium was removed from the woody tissue of leaves grown on the ligher soils whereas calcium was deposited in the tissue of leaves grown on heavier soils, with the result that the amount of calcium in the woody tissue of

TABLE 10

The relative amounts of magnesium in the woody tissue of first growth alfalfa stems and leaves at early growth and at maturity

When grown on different soil types

SOIL TYPE	EARLY STAGE, MAY 8				MATURE STAGE					
	Mgm. Mg per gm. green material		Mgm. in tissue of 1 gm. green material		Mgm. Mg per gm. green material		Mgm. Mg. in tissue of 1 gm. green material		Amount Mg added after May 8	
	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
Plainfield	.....	0.48	.....	....	.....	0.77	.....	0.16	.....	....
Coloma	0.480	0.50	0.040	....	0.476	0.77	0.073	0.04	0.033	....
Hillsdale	0.384	0.48	0.066	0.03	0.624	0.74	0.128	0.06	0.062	0.03
Fox	0.648	0.60	0.249	0.13	0.720	1.44	0.085	0.58	0.164	0.45
Brookston	0.624	0.55	0.106	....	0.408	0.69	0.003	0.18	0.103	....
Miami	0.576	0.60	0.236	0.21	0.576	0.81	0.117	0.17	0.119	−0.04

leaves grown on ligher soils was less at full bloom than in that of leaves grown on the heavier soils, except in the case of Miami soil.

Smaller amounts of calcium were present in the woody tissue of alfalfa leaves of the first crop at both stages of growth studied than was the case with the stems. Also less calcium was deposited in the woody tissue of the leaves than of the stems during the period of growth. Apparently there was a translocation of calcium from the leaves of alfalfa grown on the light sandy soils.

In table 10 are given the relative amounts of magnesium in the woody tissue of the stems and of the leaves of first growth alfalfa at early growth and at full bloom. Much smaller amounts of magnesium than of calcium were present in the woody tissue of stems at any time, and it appears that at least in stems grown on heavy soil types there was a removal of a portion of the magnesium as the plants advanced in age.

The amount of magnesium in the woody tissue of the alfalfa leaves was

usually about equal to the amount of calcium present, and in some cases the amount was even greater. Although the data are incomplete it appears that only small amounts of magnesium were deposited in the woody tissue of leaves in the latter portion of the growth period and some may even have been

TABLE 11

Relative amounts of calcium in the woody tissue of second growth alfalfa stems and leaves in early growth and in full bloom

When grown on different soil types

SOIL TYPES	EARLY STAGE				FULL BLOOM					
	Mgm. Ca in gm. green material		Mgm. Ca in actual tissue		Mgm. Ca in gm. green material		Mgm. Ca in actual tissue		Amount Ca added after July 24	
	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
Plainfield	1.90	3.03	1.03	1.49	....	....	....	....	....	....
Coloma	1.38	....	0.21	....	3.34	7.38	1.94	1.06	1.73	....
Hillsdale	1.58	2.95	0.66	1.32	....	....	....	....	....	....
Fox	1.83	3.52	0.92	1.54	3.02	7.94	1.88	3.35	0.96	....
Conover	1.95	4.10	0.80	1.76	....	....	....	....	....	....
Brookston	2.26	4.08	1.21	1.82	3.18	7.58	2.02	2.73	0.82	0.92
Miami	1.88	3.60	0.89	1.65	2.79	8.26	1.67	3.17	0.78	1.52

TABLE 12

Relative amounts of magnesium in the woody tissue of second growth alfalfa stems and leaves in early growth and in full bloom

When grown on different soil types

SOIL TYPE	EARLY GROWTH				FULL BLOOM					
	Mgm. Mg in gm. green material		Mgm. Mg in tissue of 1 gm. green material		Mgm. Mg. in 1 gm. green material		Mgm. Mg in tissue of 1 gm. green material		Mgm. Mg added after July 24	
	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
Plainfield	....	1.05	....	0.38	....	....	....	....	....	....
Coloma	0.81	....	0.04	....	1.83	1.68	0.94	0.72	0.90	....
Hillsdale	0.81	1.01	0.05	0.29	....	....	....	....	....	....
Fox	0.91	1.05	0.19	0.28	1.94	1.86	1.37	1.92	1.18	1.64
Conover	1.05	1.08	0.08	0.25	....	....	....	....	....	....
Brookston	0.91	1.03	0.13	0.32	1.92	1.69	1.23	0.90	1.10	0.58
Miami	1.15	0.96	0.29	0.30	1.89	1.37	1.05	0.34	0.76	0.04

removed. Apparently soil texture influenced the amount of magnesium deposited in the tissue at the early stage of growth, when there was more in the stems and leaves grown on heavy soil types.

Data showing the amounts of calcium in the woody tissue of second growth alfalfa stems and leaves are given in table 11. In the case of stems, soil texture did not appear to influence the amount of calcium in the woody tissue but it

did influence the amounts that were added during the final stages of growth, greater amounts being added to the stems grown on light soil types.

About equal amounts of calcium were present in the stems of first and second growth alfalfa when very young, but in the more mature plants the amount became greater in the second crop stems, and greater amounts were added during the growth period. Noticeably greater amounts of calcium were present in the woody tissue of second crop leaves during the entire growth period, and greater amounts were deposited in the tissue during the life of the plant.

TABLE 13

Moisture content of first and second growth alfalfa stems at different stages of growth and on different soil types

Per cent on dry basis

DATE OF SAMPLINGS	SOIL TYPE						
	Coloma	Plainfield	Hilldale	Fox	Conover	Brookston	Miami
First growth							
May 8	82.10	85.35	83.85	83.73	83.75	80.55	82.90
May 22	86.95	97.75	86.35	86.70	85.95	83.95	86.15
June 7	83.20	81.85	84.00	81.80	79.85	79.70	82.25
July 2	73.90	73.85	73.85	77.90	.....	76.85	72.80
Second growth							
July 24	88.20	84.15	86.90	86.05	86.10	82.05	86.05
August 7	82.90	84.80	77.85	75.25	77.25	74.75	.....
Full bloom	69.40	.....	.....	67.60	.....	67.90	68.37

Greater amounts of calcium were present in the woody tissue of second growth alfalfa leaves than in that of the stems. This is the reverse of what was found for alfalfa of the first crop.

Table 12 includes data showing the amounts of magnesium in the woody tissue of second growth alfalfa stems and leaves. Greater amounts of magnesium were present in the leaves of the young plants, but more was deposited in the tissue of the stems as the plants became older, resulting in a greater quantity in the woody tissue of the stems at full bloom. Magnesium was added to the woody tissue of both stems and leaves in every instance.

More magnesium was found in the woody tissue of the stems of the second crop at full bloom than in that of the first crop stems. In the young plants, however, there was little difference in the amounts present in the two crops and a remarkable agreement is evident in the data of tables 10 and 12 relative to this early growth.

Greater amounts of magnesium were present in the woody tissue of second growth leaves than in that of first growth leaves throughout the growth period, and more magnesium was deposited in second crop leaves as the plants became older.

Smaller amounts of magnesium and of calcium were always present in the woody tissue of both stems and leaves of the second crop of alfalfa than in that of the stems and leaves of the first crop.

Relationship of soil type to additional characteristics of the alfalfa plant

Great uniformity is shown in the moisture contents of alfalfa stems and leaves grown on the different soil types by the data presented in table 13.

TABLE 14

Moisture content of first and second growth alfalfa leaves at different stages of growth and on different soil types

Per cent on dry basis

DATE OF SAMPLINGS	SOIL TYPE						
	Coloma	Plainfield	Hillsdale	Fox	Conover	Brookston	Miami
First growth							
May 8	77.03	81.26	78.75	77.62	78.57	77.15	77.75
May 22	79.73	82.30	79.05	79.10	79.60	76.95	76.40
June 7	78.40	81.40	78.15	77.65	77.35	76.25	77.10
July 2	75.95	76.85	77.45	75.45	.....	73.60	72.70
Second growth							
July 24	82.20	76.35	81.70	80.30	79.85	78.20	79.55
August 7	80.75	79.45	78.45	74.95	78.05	75.45	.....
Full bloom	72.00	.....	.....	68.85	.....	71.65	72.05

Although the moisture content of stems and leaves grown on Plainfield soil was usually the greatest and that of stems and leaves grown on Brookston soil was usually lowest, the differences between the two were not great at any stage of growth. Although it is recognized that there were not large differences in the moisture contents of the stems and leaves grown on the several soil types, yet some interesting variations which appear to be related to soil type differences, will be pointed out in the following discussion.

Greater percentages of moisture were present in the stems than in the leaves of alfalfa when the plants were young. The moisture content of both stems and leaves decreased as the plants became older, it being noticeably less at full bloom than in the very young materials. An increase in moisture was noted on almost every soil type for both stems and leaves at the sampling

made on May 22. After this date the decrease in moisture content was quite uniform on all of the soil types.

The moisture content of the stems grown on the different soil types was about equal when the plants were very young; but there was a greater decrease in the amount of moisture in the stems grown on the light soils as the season advanced, resulting in a generally lower moisture content at full bloom in these as compared with the stems grown on the heavy soils.

Contrary to what was found for the stems of alfalfa, the decrease of moisture in the leaves as the growth period advanced was slower on the sandy soils than on the heavy soils. This resulted not only in the fact that the moisture content was higher in the leaves on sandy soils at the full bloom stage but also in the fact that the leaves on sandy soils decreased slowly enough in moisture that they contained more than did the stems at the full bloom stage. This

TABLE 15

Specific gravity of expressed juice of first growth alfalfa stems and leaves at different stages of growth

Specific gravity of distilled water = 1.000

SOIL TYPE	STAGE OF GROWTH					
	May 22*		June 6		July 2	
	Stems	Leaves	Stems	Leaves	Stems	Leaves
Plainfield	1.023	1.035	1.026	1.041	1.031	1.046
Coloma	1.023	1.037	1.029	1.044	1.028	1.054
Hillsdale	1.020	1.041	1.030	1.046	1.032	1.056
Conover	1.026	1.046	1.034	1.054	.....	.....
Fox	1.031	1.046	1.034	1.052	1.032	1.060
Brookston	1.032	1.048	1.040	1.052	1.034	1.054
Miami	1.030	1.047	1.034	1.052	1.038	1.058

* Data not obtained for first sampling.

was not true of leaves grown on the heavy soil types, whose moisture contents were always lower than those of the stems.

Noticeably greater amounts of moisture were present in the second growth alfalfa plants (table 14) than were present in those of the first growth when the plants were very young. But at the full bloom stage the amount of moisture was greater in the first growth alfalfa plants. There appeared to be no relationship between soil type and the moisture content in the second growth alfalfa. Although Brookston stems were still lowest in moisture, Plainfield stems and leaves were no longer highest.

Much greater amounts of moisture were present in the stems of young second growth alfalfa than were present in the leaves. A much greater decrease took place, however, in the moisture content of the stems during the growth period than occurred with the leaves and, as a result, the moisture content at full bloom was greatest in the leaves on all the types studied.

The specific gravity of the expressed juice of first growth alfalfa stems and leaves at different stages of growth, and its relationship to soil types

The specific gravities of the expressed juice of first growth alfalfa stems and leaves at different stages of growth are shown in table 15. Here it is evident that the specific gravity was much greater for the juice of alfalfa leaves than it was for that of stems at all stages of growth.

As the alfalfa plants became older, the specific gravity of the expressed juice of the leaves increased in an almost arithmetical progression on all of the soil types studied. This increase is rapid throughout the period of growth, and agrees rather closely with the increase noted in the calcium and magnesium content of the juice of the leaves.

An increase at early growth was observed in the specific gravity of the juice of alfalfa stems almost identical to that observed for the leaves, but on only

TABLE 16

Specific gravity of expressed juice of second growth alfalfa stems and leaves at different stages of growth and on different soil types

Specific gravity of distilled water = 1.000

SOIL TYPE	STEMS		LEAVES	
	Stage of growth			
	August 7	Maturity	August 7	Maturity
Plainfield	1.026	.....	1.040	.....
Coloma	1.021	1.040	1.036	1.072
Hillsdale	1.028	.....	1.042	.....
Fox	1.028	1.048	1.048	1.082
Conover	1.028	.....	1.045	.....
Brookston	1.030	1.044	1.050	1.068

two soil types was the increase uniform throughout the growth period. On the remaining soil types the specific gravity either increased very slowly to full bloom or decreased more or less rapidly until it was but slightly higher than that observed in the young plants. Any increase or decrease in the specific gravity of the juice of alfalfa stems did not correspond uniformly to similar increases or decreases in the calcium and magnesium content of the juice of stems as given previously, although on three of the soil types, Plainfield, Miami and Brookston, there was an agreement.

Marked differences were found in the specific gravities of the juice from stems and leaves of plants grown on the soils of different texture. Table 15 shows that the specific gravity of the juice of both stems and leaves of plants grown on heavy soils was much higher than that of stems and leaves grown on the light soils. This is in general agreement with the data obtained in regard to the calcium and magnesium content of the juice of the stems and leaves, and it would appear, therefore, that these elements were largely responsible for the

specific gravity of the juice. Deviations from this were no doubt due to the presence of other cations which probably varied in amount in the plants grown on the different soil types.

In table 16 is given the specific gravity of the juice of second growth stems and leaves, which was much higher in the full bloom stage than in the case of first crop alfalfa. There was little difference in the values of the two crops when the plants were young, and therefore the increase in specific gravity of the juice as the growth period advanced was much more rapid in second cutting plants. Here, as was found in the first crop, it appears that there was rather a close agreement between the specific gravity of the juice and its calcium and magnesium content, and that these elements were important in determining the specific gravity. This does not lose sight of the fact that other cations were also present, and these may account for the irregularities which were noted.

TABLE 17

Proportion of leaves and stems of alfalfa at budding stage on different soil types

Per cent green material

PART OF PLANT	SOIL TYPE						
	Plainfield	Coloma	Hillsdale	Fox	Conover	Brookston	Miami
Leaves	62.0	59.0	65.4	61.1	59.1	58.0	61.1
Stems	38.0	41.0	34.6	38.9	40.9	42.0	38.9

There appeared to be no relationship between soil texture and the specific gravity of the juice of leaves and stems of second cutting alfalfa.

Proportions of stems and leaves in the alfalfa plant as affected by soil type

Some variations occurred in the proportion of stems and leaves of the alfalfa plants grown on different soil types at the time buds were appearing. Widstoe (23) found that as the period of growth advanced, the percentage of leaves increased. It is noticeable in table 17 that the percentage of leaves was greater on the plants grown on Plainfield, Hillsdale, Fox, and Miami soils, but it is entirely possible that this was due to a more advanced stage of growth on these types; throughout this work, a more luxuriant growth was observed on these soil types and it may be that the budding stage was a few days more advanced than on the other types. Strength is added to this supposition by the fact that the growth was always slowest on Brookston, and here the proportion of leaves was lowest.

Considering these facts, it is probable that there was little difference in the percentages of leaves and stems grown on the different soil types and it is also evident that soil texture did not influence it.

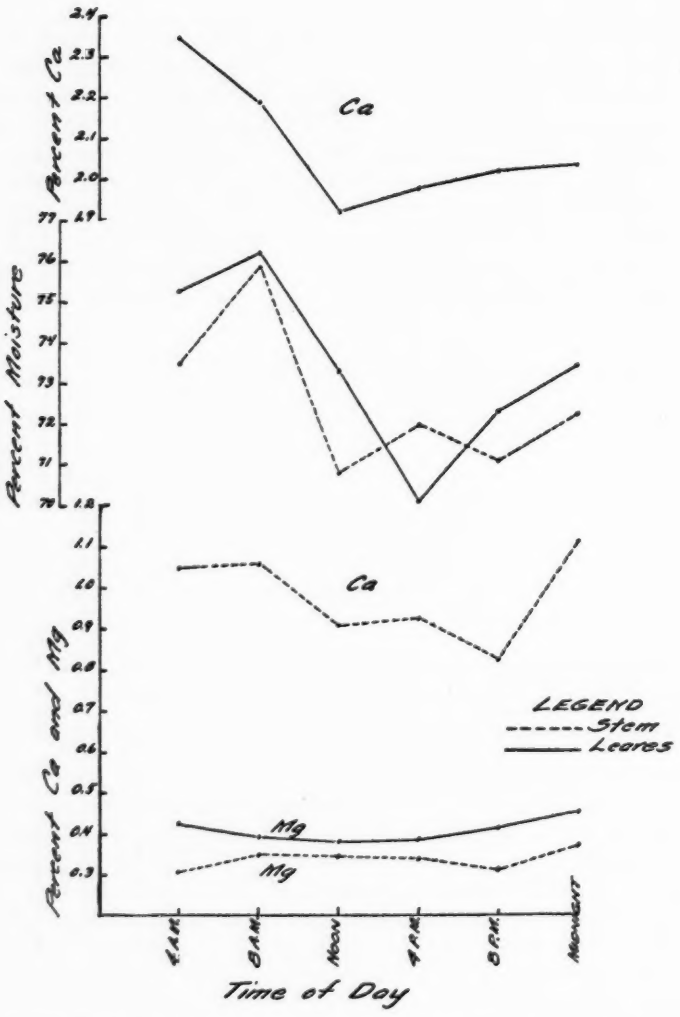

FIG. 1. THE RELATION OF TIME OF DAY TO THE CALCIUM, MAGNESIUM, AND MOISTURE CONTENTS OF ALFALFA STEMS AND LEAVES

Variations in the composition of the alfalfa plant at different hours of the day

Differences in the rate of transpiration and in the physiological activity of the plant occur at different hours of the 24-hour cycle. In order to determine what variations occur in the factors studied in this work, samples of alfalfa grown on Hillsdale sandy loam were taken at 4-hour intervals during the 24-hour day.

That considerable variation occurred in the calcium and magnesium content and in the moisture content of alfalfa stems and leaves at different times of the day is shown by figure 1. These three substances showed a remarkable correlation, a rise or a fall in one being accompanied by almost a proportionate rise or fall in the other two.

In the case of the stems a rather sharp rise in the calcium, magnesium, and moisture content took place in the period of time from 4 until 8 a.m. After 8 o'clock a marked depression occurred and continued until 4 p.m. or even until 8 p.m. During the 4-hour period between 8 p.m. and midnight, there was a sharp rise in the amounts of moisture, calcium, and magnesium present.

The moisture content of the leaves nearly paralleled that of the stems during the 24-hour period, but its relationship to the calcium and magnesium content of the leaves was not so exact as was noted for stems. During the 4-hour period from 4 until 8 a.m. there was an increase in the moisture content but a decrease in the amount of calcium and magnesium. Also during the 4-hour period between noon and 4 p.m. there was a decrease in the moisture content but an increase in the calcium and magnesium content.

At 4 p.m. the lowest moisture content was reached for the leaves and at noon the lowest content of calcium and magnesium was reached. Greater variation in the composition of the leaves took place between 4 a.m. and noon, and the least between noon and 8 p.m.

Variations occurring in the specific gravity and in the calcium and magnesium content of the expressed juice of alfalfa stems and leaves are given in figure 2. For the juice of the stems, the lowest specific gravity occurred at 8 a.m., after which there was a rise until noon and then a constant value maintained until midnight. A decrease in the calcium and magnesium content of the juice also occurred at 8 a.m., followed by a rise lasting until 4 p.m.

Greater variations took place in the specific gravity, the calcium content, and the magnesium content between 8 a.m. and noon than during any other 4-hour period.

Figure 2 also shows variations taking place in the specific gravity and in the calcium and magnesium content of the expressed juice of alfalfa leaves during the 24-hour cycle. Somewhat the same trend was taken by the varying values for the leaves as was observed for the stems, the low points occurring at 8 a.m., followed by increases during the middle of the day.

The greatest variation in specific gravity and in the calcium content occurred from 8 a.m. until noon, followed by a uniform period from noon to

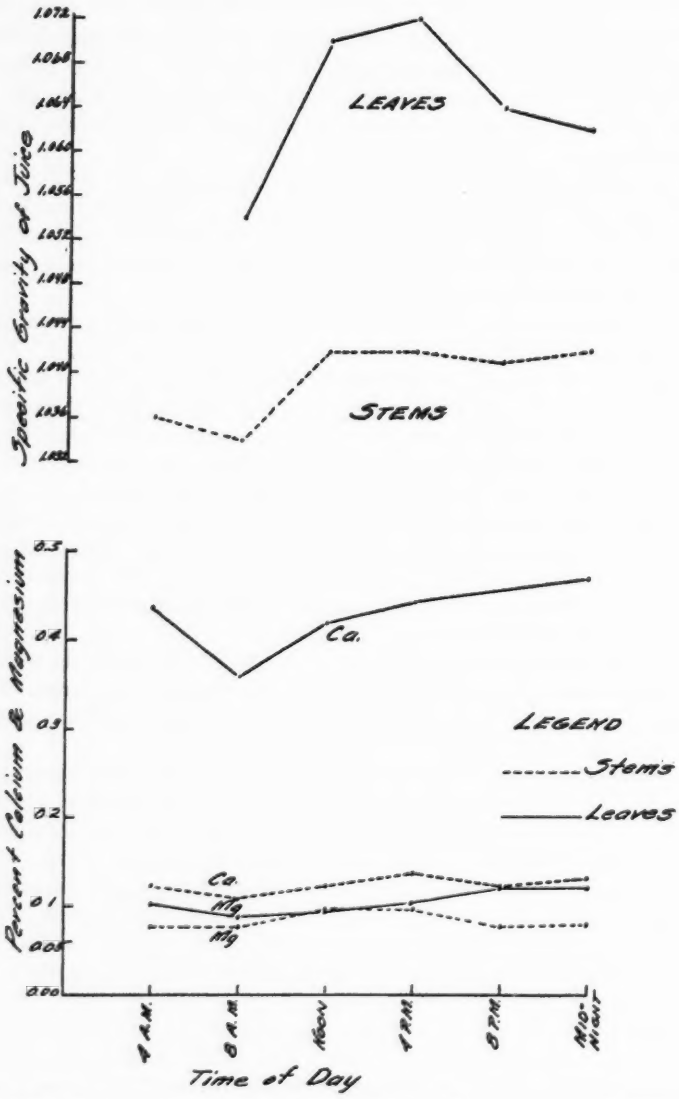

FIG. 2. THE RELATION OF TIME OF DAY TO THE SPECIFIC GRAVITY AND THE CALCIUM AND MAGNESIUM CONTENTS OF THE EXPRESSED JUICE OF ALFALFA STEMS AND LEAVES

4 p.m. The magnesium content was singularly uniform during the entire day in the expressed juice of alfalfa leaves.

The concentration of calcium and magnesium in the juice of stems and leaves varied inversely as the amounts of these present in the tissue at different times of the day. However, the variations in concentration of the juice were accompanied by like changes in the specific gravity and by unlike changes in the amounts of moisture present in the green material. Since it has been established that a large part of the calcium and magnesium present in the tissue is due to that contained in the juice, a reduction in the juice, even though accompanied by an increased concentration, would bring about a decrease of these elements in the tissue. Evidently this is what occurred to cause a decrease of the two elements in the tissue simultaneously with the decrease in moisture.

SUMMARY AND CONCLUSIONS

Alfalfa stems and leaves and the expressed juice of alfalfa stems and leaves grown on seven soil types were analyzed for calcium and magnesium at different stages of growth. The moisture content and the specific gravity of the expressed juice were determined. The proportion of stems and leaves and the effect of time of day on the composition of the alfalfa plant were determined. In addition, the amounts of calcium and magnesium present in the woody tissue of the leaves and stems free of the amounts in the liquid portion of the plants were determined in very young and in mature plants.

There were marked differences in the calcium and magnesium contents of alfalfa stems and leaves, and of their expressed juice in the plants grown on the different soil types. Likewise marked differences were found in the specific gravity of the juice of stems and leaves and slight differences in the amounts of moisture present in them when obtained from the different soil types.

Generally the calcium content was higher in the dry tissue and in the expressed juice of alfalfa stems and leaves grown on the heavy soil types studied. Sandy loams, however, gave a higher calcium content in these than did the heavier loams.

Soil type had less influence on the second crop than on the first and the effect of soil texture became practically negligible in the second crop. It would appear that with the continued growth of the plants, changes which equalized the facilities with which the plants were able to obtain their supply of calcium and magnesium, had occurred in the soils, resulting in a uniformity of composition (in respect to these elements) of the plants from the different soil types.

No consistent relationship appeared to exist at any time between the texture of the soil and the magnesium content of the alfalfa plant.

More calcium was present in the tissue and in the juice of the alfalfa leaves than in the tissue and in the juice of the stems.

About equal amounts of magnesium were present in the tissue of leaves and stems and also in their juice.

More calcium than magnesium was always present in the tissue and the juice of both the stems and the leaves.

There was either an increase or a decrease in the calcium content of the tissue and of the juice of first growth alfalfa stems as the plants became older, but there was only a decrease in the calcium content of the tissue and juice of second growth stems as the plants advanced in age.

The magnesium content of the tissue of first and second growth alfalfa stems decreased as the plants became more mature.

The calcium content increased in the tissue and in the juice of leaves of the first and second crops of alfalfa as the plants grew older.

With the advance of the growth period, the magnesium content increased in the tissue of first growth alfalfa leaves but decreased in the tissue of the leaves of the second growth.

Greater concentrations of magnesium were usually present in the juice of more mature leaves and stems than in that of the young leaves and stems of both the first and second crops.

The calcium content was higher in the stems and in the young leaves of second growth alfalfa than in the first growth. The content of calcium was higher in mature leaves of first crop alfalfa than in the mature leaves of the second growth.

About equal percentages of magnesium were present in the stems and leaves of first and second growth alfalfa and likewise the concentrations of calcium and magnesium were about equal in the juice of stems and leaves of both cuttings of alfalfa.

Large amounts of calcium were deposited in the woody tissue of alfalfa stems as the plants advanced in age, and greater amounts were added to the stem tissue of the second growth than to that of the first growth.

In the first crop of alfalfa, calcium was added to the woody tissue of the leaves on some of the soil types as the growth period advanced, whereas on other soil types it was removed from the woody tissue. In the second crop calcium was always added to the woody tissue of the leaves.

Greater amounts of calcium were usually present in woody tissue of alfalfa stems than in that of the leaves, and more was deposited in the woody tissue of the stems than in that of the leaves as the period of growth advanced.

Soil type influenced the amount of calcium in the woody tissue of alfalfa stems and leaves. In the early stage of growth the calcium content was low in the woody tissue of stems grown on light soil and low in the tissue of the leaves grown on heavy soils, whereas at maturity the calcium content of the woody tissue of stems was low on the heavy soils and in that of leaves it was low on the light soils.

Much smaller amounts of magnesium than of calcium were present in the woody tissue of first growth alfalfa stems, whereas the amounts of calcium and magnesium were about equal in the woody tissue of leaves.

In second growth alfalfa, greater amounts of calcium than of magnesium were present in the woody tissue of both stems and leaves.

In first growth alfalfa, the amount of magnesium in the woody tissue of stems and leaves was either decreased or increased as the plants became older. In the second crop it always increased in both stems and leaves.

The amount of magnesium in the woody tissue of stems and leaves of both the first and the second crops of alfalfa varied on the different soil types but it did not appear to depend on soil texture.

Greater amounts of magnesium were present in the woody tissue of stems and leaves of second growth alfalfa than in that of the first crop. It appears that the calcium and magnesium present in the plant material were largely due to that contained in the juice of the plant and not incorporated in the tissue itself.

The moisture content of alfalfa stems and leaves decreased as the plants became more mature.

More moisture was present in the stems than in the leaves of alfalfa when the plants were young but it became about equal, or slightly greater in the leaves, as the plants advanced in age, especially in the second crop.

Greater moisture content occurred in the stems and leaves of the second crop than of the first crop of alfalfa when the plants were young, but when the plants became older there was more present in first growth stems and leaves.

Soil type apparently was related to some changes which occurred in the moisture content of alfalfa as the growth period advanced.

Greater specific gravity was possessed by the expressed juice of alfalfa leaves than of stems.

The specific gravity of the juice of alfalfa stems increased for a period and then usually decreased to maturity. That of the juice of alfalfa leaves increased in an arithmetical progression during the growth period.

The specific gravity of the juice of both stems and leaves was noticeably greater in plants on heavy soil types.

The specific gravity of the juice of second growth alfalfa stems and leaves was much greater than that of the juice of first growth stems and leaves.

The specific gravity of the juice of the stems and leaves of both crops appeared to conform very closely to the calcium and magnesium content, showing that these cations were important in determining it.

The ratio of stems to leaves was about equal on the different soil types at the budding stage.

The calcium, magnesium, and moisture content of alfalfa stems and leaves varied at different hours during the day. This was also true of the calcium and magnesium contents and the specific gravity of the expressed juice of stems and leaves.

The percentages of calcium and magnesium in the tissue of stems and leaves varied almost inversely as the concentration of these in the juice of the stems and leaves at different hours of the day, probably because of differences in the amounts of juice present in the tissue as a result of changes in the moisture content.

The most satisfactory time to obtain alfalfa samples in order to eliminate

variations due to time of day lies between noon and 4 p.m. The least satisfactory time lies between 8 a.m. and noon.

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A NEW, SIMPLE, AND RAPID METHOD FOR DETERMINING THE MOISTURE EQUIVALENT OF SOILS, AND THE ROLE OF SOIL COLLOIDS ON THIS MOISTURE EQUIVALENT

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In a communication (1) published nine years ago, the following statement was made:

> Water is one of the best indices of the physical characteristics of soil. Texture, structure colloidal and organic contents, surface activation, etc., tend to be revealed by the behavior of the soil toward water. Heat of wetting, moisture retentiveness, unfree water, etc., are mainly the resultant and expression of these characteristics.

After nine years of further study along these lines, the writer still believes that water affords probably the best index of the physical characteristics of the soil. The behavior of a soil toward water probably gives truer and more comprehensive composite information concerning the physical characteristics of that soil than the behavior of the same soil toward any other agent. This is probably due to two main factors: first, water, besides being the most natural and universal reagent, is also the chief natural agent by which the soil has been formed; second, most of the physical properties of the soil run parallel with its behavior toward water—for instance, the finer the texture of a soil, the greater is its hygroscopic water, absorption-adsorption of water, water holding capacity, capillary movement of water, evaporation of water, unfree water, wilting coefficient of plants, and shrinkage of soils. In the same parallel direction the greater the organic matter content is in a soil, the greater will be its hygroscopic water, absorption-adsorption of water, water holding capacity, capillary movement of water, evaporation of water, unfree water, wilting coefficient of plants, and shrinkage of soils. Here, therefore, the texture of mineral soils and the content of organic matter are not opposed in the behavior of a natural soil toward water.

On the other hand, if a single property of soils, such as plasticity, is used as an index of the general characterization of soils, we find that texture of mineral soils and organic matter content are opposed, and consequently plasticity and the other physical properties of soils do not run parallel, as in the case of water. For instance, the finer the texture is in a mineral soil, the greater will be its plasticity. On the other hand the greater the organic matter content is in a soil, the smaller will be its plasticity.

After the development of the hydrometer method (2, 4) for determining the colloidal content of soils and also for making a mechanical analysis of soils in only fifteen minutes, some single value factor was desired which would be simple, rapid, and reliable to accompany and complement the hydrometer method. Furthermore, it was desired to see whether the results of the hydrometer method could be summarized in a composite form in some single value factor.

In the belief, as already stated, that in the agent of water, or in the relationship of soil to water, resided the greatest possibility of discovering this single value factor, all efforts were concentrated in this direction.

The relationship between soil and water that was first considered, was the maximum total water holding capacity of soils. It was thought that if a method such as that of Hilgard (7), could give a reliable and truly comparable value of water holding power between different soils, it would serve as an excellent single value factor of summarizing most of the physical properties of soils. Unfortunately, however, Hilgard's method for determining the maximum moisture holding power of soils is most unreliable and extremely erroneous, and should not be used in its original form. The surface tension forces on the bottom of the cup tend to prevent a thorough drainage of the soil, and a considerable and variable amount of water is held back.

The next relationship of soil to water that was considered and carefully examined was the moisture equivalent factor as proposed and determined by Briggs and McLane (5, 6). This relationship would seem to afford a splendid single value factor. But unfortunately, here again, the method for obtaining the relationship is not accurate and probably does not give a truly comparable result for the soils of different textures. Here are the difficulties that have been encountered with the method at this laboratory: 1. In the case of heavy clays, especially the sticky type, the centrifugal force compacts the layer of soil to such an extent that the water is not thrown out but collects at the top of the layer. Consequently the results of such soils are not truly comparable with those of soils which allow the water to get out easily by the centrifugal force. That the results for different soils may not be truly comparable, would seem to be borne out by the examination of some data recently published by Professor Lebedeff (8). Professor Lebedeff employed widely different centrifugal speeds to obtain the moisture equivalent of soils. When soil 1 (table 3), which must be a clay, and soil 7, which is Sassafrass silt loam, were centrifuged for 50 minutes at 400 g (*g* is the acceleration of gravitation), soil 1 had a moisture content of 47.9 per cent and soil 7, 25.6 per cent. Now when these two soils were again centrifuged one minute at 70,000 g, the moisture content of soil 1 was reduced to 34.6 per cent, whereas the moisture content of soil 7 was reduced to only 7.1. By calculating the difference of moisture of the same soils at the two different speeds of centrifuging, it is found that soil 1 lost only 27.76 per cent more water when it was centrifuged at 70,000 g, while soil 7 lost 72.30 per cent. It is common knowledge that coarse textured soils

hold water with much smaller forces than fine textured soils. Consequently it would be logical to expect that the coarse textured soils would lose their water more easily at 400 g than the fine textured soils. Therefore, soil 7 should have lost proportionally much greater water at this force than soil 1 and at the centrifugal force of 70,000, soil 1 should have lost much more water than soil 7. But the results are just the opposite, and the explanation for this would seem to be that the clay soil (no. 1) becomes so compact as a result of the centrifugal force, that it is mechanically unable to give up all the water that it should under those forces, whereas soil 7 being of a coarser texture, does not present the same mechanical difficulty. Consequently it loses all the water that it should under those gravitational forces.

Several other single value factors were next considered, such as the wilting coefficient, hygroscopic coefficient, and vapor adsorption, but they were all finally abandoned as being impractical either because they were not sufficiently accurate and reliable, or because of the enormous length of time they required, or both.

It was finally decided to search for some new method to be used as a single value factor to accompany and complement the hydrometer method, a method that should still have water for its basis.

It seemed at the outset that a possible combination or modification of the maximum moisture content method and the moisture equivalent method might yield the desired new method. It was thought, therefore, that instead of applying centrifugal force to pull out the water from the soils, the same thing might be better accomplished by suction or vacuum forces. It was argued that the suction or vacuum forces would not compact the soils, and consequently the water would come out as easily in clay soils as in sandy soils, and the results, therefore, would be truly comparable for these different textured soils.

It is the object of this paper, therefore, to present a new, simple, and reliable method for determining the moisture equivalent of soils, which might be used as a single value factor and also to show what relationship the results of this method bear to the results obtained by the hydrometer method in the mechanical analysis of soils.

DESCRIPTION OF METHOD

The principle of the method is based upon the pulling out of water from soils by suction or vacuum forces. With this principle in mind one can use almost any method, provided it is standardized so as to give consistent and comparable results. The method that was worked out and finally adopted consists of connecting a Büchner funnel with a suction flask, placing a sample of soil into the funnel with a filter paper at the bottom, thoroughly soaking the soil with water, connecting the flask to the suction pipe on the faucet, and then allowing the suction force from the running water to operate on the soil for a definite length of time. The actual set-up of the apparatus is shown

in plate 1. The funnel is small—4.3 cm. in diameter and 2 cm. deep. The filter paper that fits this funnel is 4.25 cm. The funnel was about three-fourths filled with soil, then filled to the top with water. Water was added until the soil seemed to be completely soaked. Then the suction was applied to the soil and more water added to it until it was well settled. The suction pulled the water from the soil very rapidly, and after the first four or five minutes the water drained very slowly. For purposes of comparison, a period of 10 minutes, beginning when all the standing water had disappeared from the top of the soil, was allowed for all soils to drain under suction. Although the water did not stop draining at the end of 10 minutes, it slowed down so much that two minutes or longer were necessary for one drop to come through. Many trials showed that if a soil was drained for much longer periods, in some cases 50 minutes, the results would not be very different, provided evaporation was prevented.

It was found that it was not necessary to take a definite quantity of the various soils. For trials, the amount of soil used was varied considerably but the results did not show any definite relationship to the amount of soil used.

In order to prevent evaporation during the suction process, the funnel was covered with a moist thick cloth. This moist cloth served two purposes—prevented direct evaporation, and tended to moisten the air that was drawn into the soil.

The heavier types of soil have a tendency to crack when they are drained, and it would seem that this might affect the results. Investigation showed, however, that this cracking has no apparent effect on the results, as the same results are obtained when the cracks are prevented from occurring or being filled with extra soil.

Probably the two factors that are likely to cause the most error or disagreement in the results are the preparation of the soil sample and the temperature of the water.

As would be expected, it was found that very fine grinding of the soil sample increased its water retaining power, and in some soils much more than in others. The soil samples, therefore, should be used as much in their natural textural condition as possible. The practice that was followed and one that seems to be an excellent one, was to place lumps of the soil in the funnel and then let the water slack these lumps. In this way the soils tended to retain their natural texture, and errors arising from this factor were greatly diminished. Where it is necessary to screen, the soil should be broken up with the fingers.

Although it has been stated that the soils should be in as natural a condition as possible, it was found that they have to be dry to be used satisfactorily. This is due mainly to the fact that in the moist condition the soils do not slack (7) and consequently do not become thoroughly soaked. Hence, the soils should always be air-dried before using.

The temperature of the water, both in the soil and in the flask, has some

influence on the results. This would be naturally expected because temperature affects both the viscosity of water and the degree of vacuum produced. It is well known that the lowest exhaust pressure obtainable is usually considered to be limited by the vapor pressure of water. The best and most consistent results, therefore, were obtained when the temperature of the water remained about the same for the different experiments. Probably the best way to maintain an even temperature is to let the tap water run for

TABLE 1

Percentage of moisture equivalent, colloidal content, and relationship between these two sets of results for the various kinds of soil

SOILS	PERCENTAGE OF COLLOIDS	PERCENTAGE OF WATER	RATIO: $\frac{\text{WATER}}{\text{COLLOIDS}}$
	per cent	*per cent*	
Strongs sandy loam A_1	10.7	5.8	0.557
Strongs sandy loam B_1	27.00	14.02	0.519
Calumet sand	8.70	5.60	0.644
Michigan sand C	8.5	5.74	0.675
Michigan sand C	14.0	9.27	0.662
Fox loam B_2	18.08	11.95	0.657
Onaway loam A_1	11.69	7.42	0.634
Stalwart loam A_1	24.22	12.62	0.521
Ontonagon silt loam A_2	63.82	32.70	0.512
California Yolo clay loam	53.94	35.10	0.651
California Yolo clay	56.80	35.16	0.618
Brookston clay loam A_2	38.90	22.35	0.573
Greenville clay loam B	46.30	23.63	0.510
Cecil clay loam B	61.50	36.60	0.595
Manor schist loam B_1	46.00	31.75	0.689
Manor schist loam B_2	32.4	22.45	0.691
Michigan silt loam	36.00	19.00	0.528
Wabash clay	54.20	38.50	0.710
Cass clay	44.00	29.00	0.659
Minnesota Clyde silt loam	36.00	26.15	0.713
Bremer clay	55.40	38.20	0.689
Minnesota Carrington silt loam	51.00	35.00	0.686
Average			0.6224

a while until it reaches its normal temperature and then use this water for soaking the soil as well as for the suction purpose.

As already stated, the vacuum pressure attained in a water jet pump is considered to be limited by the vapor pressure of the water. The pressure or the force with which the water jet runs also affects the vacuum pressure. As a rule, however, the pressure of the water in any one water system is not likely to vary very considerably from day to day and if the running water is allowed to attain its normal temperature, there should not be much error

caused by this vacuum pressure system recommended here. In the different laboratories the pressure and temperature of the water may be different, but as long as they remain about the same for the different experiments, the comparison for the soils studied will be true.

The vacuum pressure that was obtained in the water system in this laboratory was about 20 mm. and remained quite constant from day to day. The temperature of the tap water was about 15°C. Consequently all the experiments received about the same degree of suction.

The method is quite rapid. The longest time in the procedure is taken up in soaking the soils. The length of time spent may be greatly reduced, however, by using two or three sets of apparatus, so that while one soil is being suctioned, one or two soils are being soaked. With the exception of some unusual soils, about 20 minutes is sufficient for them to soak quite completely (3).

Of course it is probably needless to state that this method is empirical, but an empirical method, if it is reliable reduces to a common basis and gives a true comparison, is as valuable as an absolute method as far as the real comparison is concerned.

It appears from the study this method has received, that it is quite reliable and gives a fairly true comparison of the moisture equivalents or the comparative water holding powers of the different soils. It also appears to give a truer comparison between the different textured soils than the Briggs and McLane method, and it is also simpler, more practical, and infinitely more available. If all the precautions stated above are observed, the results can be duplicated within about one per cent.

EXPERIMENTAL DATA

Table 1 shows the percentage of water that the different types of soils retain under the experimental conditions already set forth, the percentage of colloidal material of these soils as determined by the hydrometer method at the end of 15 minutes, and also the ratio of the percentages of moisture and of colloids for each soil.

The percentages of water and of colloids vary widely for the different soils, and both tend to be high with fine textured soils and low with coarse textured soils. The significance of these two sets of results, however, is revealed in the ratio figures. Here it is shown that when the percentage of water is divided by the percentage of colloids a ratio is obtained which, taking all factors into consideration, is remarkably close for all the different types of soils; such as coarse sand, heavy clay, high silt content, high organic matter content, no organic matter content, and high iron content. This ratio varies from 0.510 to 0.713, with an average of 0.6224. The majority of the soils have a ratio close to this average. If the vacuum pressure method for obtaining the moisture equivalent and the hydrometer method for obtaining the colloidal content would give perfectly true results for all soils, this ratio

would be even closer. It is known, however, that with some rather unusual soils these methods may not give exactly true results. For instance, if a soil is exceedingly difficult to disperse, the hydrometer method will not give its true colloidal content. Furthermore, an error of 2 or 3 per cent in either method makes quite an appreciable difference in this ratio. These variations in the ratio should not prevent the realization and acceptance of the fact that there is a real and unmistakably close relationship between the colloidal and the moisture contents of a soil.

The results also show that the controlling factor in the moisture equivalent is the colloidal content because there is no relationship between the coarse silt, sand and the moisture equivalent.

The moisture equivalent as obtained by the new vacuum pressure method and the colloidal content as obtained by the hydrometer method, besides showing a real and interdependent relationship, also show that the new moisture equivalent method is reliable, accurate, and tends to give true comparative results for the different kinds of soils.

This relationship reveals one more significant thing, that the hydrometer method for determining colloids, the heat of wetting method for determining colloids (2) and the vacuum pressure method for determining the moisture equivalent of soils are fundamentally sound and correct; at least they give true comparative results for all soils. When these three different methods, which are based upon entirely different principles, agree so remarkably well in their results on all kinds of soils, what better proof is needed of their fundamental soundness and correctness? The remarkable agreement of these three entirely different methods is exceedingly significant.

Since the relationship between colloidal content and moisture equivalent is so close, when one result is known the other can be calculated from the average ratio. For instance, one knows the colloidal content, the moisture equivalent can be obtained by multiplying the colloidal content with the ratio. If, on the other hand, only the moisture is known, then the colloidal content can be obtained by dividing the percentage of moisture by the ratio. Those who are using the hydrometer method can safely employ the factor 0.6224 for determining the comparative moisture equivalent of soils without experimentally determining this factor themselves.

From the foregoing experimental results, it becomes very apparent that both the new moisture equivalent method and the hydrometer method are sound and reliable for "single value" determinations. Of the two, however, the hydrometer method is by far the better. In the first place, besides giving the moisture equivalent of soils, it gives also the mechanical analysis of soils, which includes the percentage of sand, silt, and colloids or clay. When the mechanical analysis is known, much information is known about many other properties of soils. Secondly, the hydrometer method is more absolute than the new moisture equivalent method; that is, different workers will get the same result on any one soil under a variety of conditions if directions are

closely followed, whereas with the moisture equivalent method the different workers may not get the same result on any one soil, because they may be dealing with different temperatures and different vacuum pressures. The results of all soils in any single laboratory, however, will be truly comparable.

The hydrometer method for the study of soils offers greater opportunities and possibilities than have been realized.

SUMMARY

A new method has been developed for determining the moisture equivalent or comparative moisture holding power of soils.

The principle of this method is based upon the pulling of water from the soil by vacuum pressure forces instead of by centrifugal forces.

The method is simple, rapid, accurate, reliable, and infinitely more available than the centrifugal method.

The results obtained by this method show that there is a remarkably close relationship between the moisture equivalent and the colloidal content of soils as determined by the hydrometer method. There is, however, no relationship between coarse silt and sand and the moisture equivalent.

It is shown that the moisture equivalent or comparative moisture holding powers of the different soils can be indirectly determined by the hydrometer method.

It is also shown that the hydrometer method may be used to obtain "single value" factors for summarizing the various physical properties of soils.

The hydrometer method has inherently great possibilities for the study of soils.

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PLATE 1

Main Apparatus Used in Determining the Moisture Equivalent of Soils

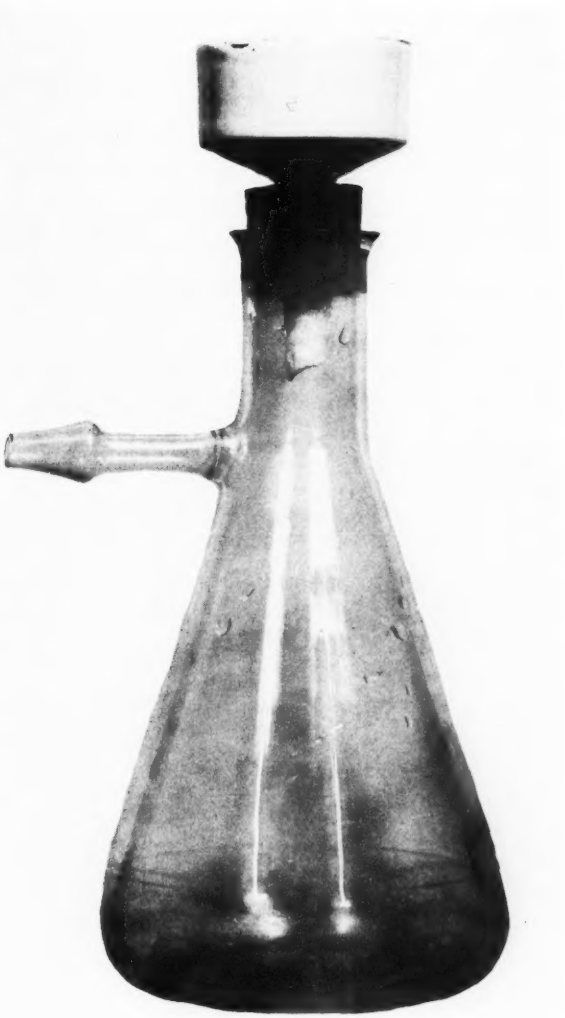

FIG. 1

REPAIR OF SOIL FILTER TUBES

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It is the common experience of soil analysts that the Chamberland-Pasteur unglazed porcelain filter tube used in making aqueous extracts of soils breaks rather easily. The break usually occurs near the juncture of the unglazed tube and the glazed nipple. The tube may be easily and inexpensively repaired by slipping a piece of stout rubber tubing of 20 mm. inside diameter

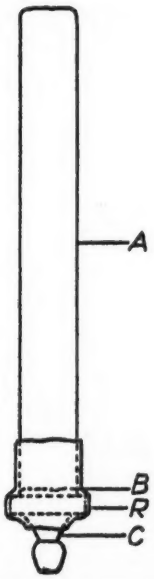

FIG. 1. SHOWING METHOD OF REPAIRING SOIL FILTER TUBES
A = unglazed filter tube; B = break; C = glazed nipple; R = rubber tubing

over the nipple and tube, as shown in figure 1. The air pressure used in filtering effectively seals the tube against leakage. Tubes so repaired are fully as serviceable as unbroken tubes and are less susceptible to further breakage. Chamberland-Pasteur filter tubes cost about $2.65 each but can be repaired with about 5 cents worth of rubber tubing.

THE USE OF DEXTRINE IN THE ISOLATION AND IDENTIFICATION OF AZOTOBACTER CHROOCOCCUM

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It is generally conceded that species of Azotobacter are fairly difficult to isolate in pure culture from the soil. I have in many cases found it exceedingly difficult to separate Azotobacter from certain non-spore-forming gram-negative rods (*Bacterium radiobacter?*), and from gram-positive spore-formers, using the ordinary Ashby's agar or other nitrogen-poor mannitol media. I have also found that many strains of Azotobacter showed either no blackening, or showed it only after prolonged incubation. Formerly I thought that I was justified in considering these non-chromogenic strains as species other than *A. chroococcum*.

Recently while using Baldwin and Fred's (1) nitrate dextrine medium in the study of many strains of the so-called *B. radiobacter*,[2] I noticed an intense jet black coloration within a week or so, often in a few days, when Azotobacter was planted on this medium. This fact led to the substitution of dextrine for mannitol in Ashby's agar, and it was found that after preliminary enrichment in Ashby's or Lipman's mannitol solution *Azotobacter chroococcum* could be isolated very readily from dextrine agar plates streaked from the enrichment flasks. Impure colonies were easily avoided. The dextrine agar slant cultures picked from the dextrine agar plates were again streaked on dextrine nitrate agar to test for purity. *B. radiobacter* and most spore-formers grow readily on this medium and any contaminant is easily noticed, since pure cultures of *Azotobacter chroococcum* showed only black colonies. Undoubtedly there are species of Azotobacter other than chromogenic ones, but as yet I have never isolated one which did not produce a black pigment on dextrine agar, particularly if nitrate was also present.

The use of dextrine nitrate agar thus not only facilitates the isolation of *Azotobacter chroococcum*, but also prevents one considering many strains as non-chromogenic. Many strains of *Azotobacter chroococcum* have been isolated in this way without the failures formerly encountered.

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[2] I inadvertently misquoted Baldwin and Fred in a former article (*Soil Sci.* 25: 195–205, 1928) as saying in effect that "this organism (*B. radiobacter*) can be readily distinguished from all strains of the nodule bacteria by the large amount of acid produced from dextrine by *B. radiobacter*." What they actually wrote was "*B. radiobacter* may be distinguished from any of the root nodule bacteria by its strong acid fermentation of dextrin," quite another thing, since only a possibility is implied, not a certainty as I attributed to them.

Recently I had a portion of Omelianski's (2) monograph on nitrogen fixing bacteria translated[3] and was surprised to find that Professor Omelianski and other Russian investigators, had been using dextrine for a number of years for the purposes enumerated, but I do not know of laboratories elsewhere where it is in use.

It was with the idea of calling the attention to this carbohydrate of any other workers who are not now using dextrine, that this note was written. Difco brand of dextrine was used, but no doubt other highly purified products would suffice.

REFERENCES

(1) BALDWIN, I. L., AND FRED, E. B. 1927 The fermentation characters of the root nodule bacteria of the Leguminosae. *Soil Sci.* 24: 217–230.

(2) OMELIANSKI, B. L. 1923 Fixation of Atmospheric Nitrogen by Soil Microorganisms (Russian), Petrograd.

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[3] I am grateful to Dr. Helen Sorokin for translating a portion of Omelianski's monograph from the Russian.

BOOK REVIEW

Laboratory Manual of General Microbiology with Special Reference to the Microorganisms of the Soil. By Edwin Broun Fred and Selman A. Waksman. McGraw-Hill Book Co., New York. 1928. Pp. 145, fig. 19.

In 1911 there appeared two excellent laboratory manuals dealing with soil bacteriology, those of Lipman and Brown and of Löhnis. Soon after, these were followed by three others, by Burgess, by Whiting, and by Fred. No field of bacteriology has been so well served with worthy laboratory manuals as has soil bacteriology, and of these manuals, that of Fred is in many ways the best. It is very widely used, and many of the younger workers got their first training from Fred's manual rather than from, or in spite of, text-books and professors. These books are now hopelessly out of date—that of Löhnis has been revised but not as yet translated into English—and it was with more than a little pleasure that teachers and investigators received the news that Fred's manual was being revised.

The new book, however, is more than a revision. In spite of the title, it is a soil microbiology manual, which for 1928 is a worthy successor to the 1916 book. It contains also many of the excellent methods summarized by Waksman and co-authors in Abderhalden's Handbuch. The emphasis in December 1928, is not primarily on "nitrogen fixation and all that sort of thing," but covers the whole soil population of microörganisms and their activities. The special interests of neither of the authors have received undue emphasis, but together they have made a splendid selection of culture media formulae and laboratory exercises. Like the 1916 book, this manual is divided into three parts, one of which gives formulae of 111 well selected media, another of which gives in outline the necessary qualitative and quantitative chemical methods, and the last part of which deals with laboratory exercises as such. In addition five pages of staining technique are given.

In spite of the excellent qualities of the manual, candor requires that certain small defects be mentioned which detract somewhat from its value. In general the book is exceedingly well arranged, but in a few places it is not. For instance, the preparation of phenoldisulfonic acid is given on page 60, but the use of it a few pages later. Likewise the aeration method of NH_3 determination is given on page 63 with other chemical methods, but the base exchange method on page 127 with the experiments. The preparation of methyl red is not described with the rest of the indicators. As was said, the selection of exercises and media is excellent. The reviewer, however, would like to have seen the more accurate Rothamsted methods and tables for counting soil protozoa given. Certainly the use of solid media for protozoa

should have been insisted upon. The new Foreman method, at once simple and accurate, for determination of amino acids, might have been given mention. Although, perhaps it ought not to be necessary, it might have been advisable to mention the possible loss of NH in each medium of a fairly high pH which contains an ammonium salt. There are very few misprints or mistakes. *Clostridium pastorianum* is the spelling originally used by Winogradsky. The term "thermostat" on page 24 is incorrectly used. It is doubtful whether the method of determination of hemicelluloses on page 77 is even approximately accurate. These points, however, are of minor importance and are perhaps partly due to the dual authorship.

Of course the practicability of a manual can be determined definitely only after it has been used for some time and has been tried out on classes of students. The reviewer ventures the opinion, however, that this one will prove, if rightly employed, as useful as Fred's 1916 manual did. No investigator or teacher who even dabbles in soil microbiology should try to get along without a copy of the manual by Fred and Waksman.

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